GJO–2002– 343–TAR

Hanford 200 Areas Spectral Gamma Baseline Characterization Project

216-B-8 Crib and Adjacent Sites Waste Site Summary Report

August 2002

U.S. Department of Energy

Work Performed Under DOE Contract Number DE–AC13–96GJ87335 for the U.S. Department of Energy

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Prepared for
U.S. Department of Energy
Idaho Operations Office
Grand Junction Office
Grand Junction, Colorado

Prepared by
S.M. Stoller Corp.
Grand Junction Office
Grand Junction, Colorado

Approved for public release; distribution is unlimited.
Work performed under DOE Contract No. DE-AC13-02GJ79491.

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Prepared by:

Paul D. Henwood — 8-27-02

P.D. Henwood — Date
S.M. Stoller, Hanford

Concurrence:

8/27/02

R.G. McCain, Hanford Technical Lead — Date
S.M. Stoller, Hanford

C.J. Koizumi — 08/29/02

C.J. Koizumi, Technical Lead — Date
S.M. Stoller, Grand Junction Office

Approved by:

W.D. Steele — 8/29/02

W.D. Steele, Project Manager — Date
S.M. Stoller, Hanford

09.03.02

J.M. Silko, Project Manager — Date
U.S. Department of Energy
Richland Operations Office

Executive Summary

The U.S. Department of Energy Richland Office (DOE-RL) tasked the DOE Grand Junction Office (DOE-GJO) to conduct a baseline characterization of the gamma-ray-emitting radionuclides distributed in vadose zone sediments in the vicinity of waste sites in the Central Plateau (200 East and West Areas) of the Hanford Site.

The Spectral Gamma Logging System (SGLS) was used to collect data in existing boreholes and monitoring wells, as well as, perform geophysical logging of new boreholes and wells drilled as part of ongoing site investigation projects. This system uses a high-purity germanium (HPGe) detector to acquire high-resolution, gamma-energy spectra for the detection, identification, and quantification of gamma-emitting radionuclides.

This report documents SGLS results obtained from 19 vadose zone boreholes, 10 Resource Conservation Recovery Act (RCRA) non-compliant groundwater wells, and 3 RCRA-compliant groundwater wells located northeast of the B-BX-BY Waste Management Area (WMA). This area includes three major liquid waste sites where existing boreholes are available. These sites are the 216-B-7A&B Cribs, the 216-B-8 Crib and Tile Field, and the 216-B-11A&B Reverse Wells.

Cesium-137 (^{137}Cs), cobalt-60 (^{60}Co), uranium-238 (^{238}U), uranium-235 (^{235}U), and europium-154 (^{154}Eu) were detected in the boreholes and groundwater wells in the vicinity of these sites. The predominant contaminant detected was ^{137}Cs, which was measured at a maximum concentration of 150,000 picocuries per gram (pCi/g). In general, contamination that appears to be directly associated with a specific waste site was observed at log depths less than 150 feet (ft), although historical gross gamma logging suggests contaminant breakthrough to groundwater may have occurred at some sites prior to 1959.

In addition to contamination identified at the three major sites, two areas of contamination were identified that do not appear to be directly associated with these sites. Uranium contamination was identified at a point southeast of tank BX-102 in the BX Tank Farm that trends approximately 500 ft to the east-northeast. This area of contamination was detected as deep as the top of the water table and appears to have migrated through the vadose zone. ^{60}Co and ^{137}Cs contamination was identified throughout the deep vadose zone in the area northeast of the WMA. This contamination was detected just above the current groundwater level and was also detected within the groundwater. However, it is only observed in RCRA non-compliant groundwater wells that were drilled in the 1950s. RCRA-compliant groundwater wells drilled since the early 1990s do not exhibit this contamination. The ^{60}Co and ^{137}Cs are probably the result of historical groundwater contamination that may have originated from the BY Cribs. The ^{60}Co and ^{137}Cs observed in the groundwater wells drilled in the 1950s have been hypothesized to be associated with rust or scale on the inside of the steel casing.

Contaminant migration in the vadose zone is influenced by the complex stratigraphy of the Hanford formation. The Hanford H1/H2 contact, a potential spreading surface, was correlated between boreholes to help predict the direction of lateral migration in the vadose zone.

Recommendations include installation of additional boreholes to better define areas of known contamination, as well as, assessment of minor waste sites in the area that have not yet been characterized.

1.0 Introduction

The Hanford 200 Areas Spectral Gamma Baseline Characterization Project team deploys borehole geophysical logging equipment to measure naturally occurring and anthropogenic radionuclides in the subsurface in the vicinity of 200 Area waste sites. The following sections provide brief discussions of background, project purpose and scope, and project objectives.

1.1 Background

The U.S. Department of Energy (DOE) Hanford Site encompasses approximately 1,450 km^2 (560 mi^2) in the Columbia Basin of south central Washington State. Beginning in World War II, the Hanford Site was involved in production of plutonium to support the national nuclear weapons program. The Hanford Site is subdivided into a number of operational regions identified as the 100, 200, 300, and 1100 Areas (Figure 1). In 1989, the U.S. Environmental Protection Agency (EPA) placed these areas on the National Priorities List (NPL) pursuant to the *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA). The 200 Areas, located on a plateau near the center of the Hanford Site, consist of the 200 West Area and 200 East Area, which include waste management facilities and inactive irradiated-fuel reprocessing facilities, and the 200 North Area, which was formerly used for interim storage and staging of irradiated fuel.

1.2 Purpose and Scope of Project

The goal of the DOE Grand Junction Office (DOE-GJO) Hanford 200 Areas Spectral Gamma Baseline Characterization Project is to collect data from existing boreholes and determine the present nature and extent of contamination associated with gamma-ray-emitting radionuclides distributed in the subsurface in the vicinity of 200 Area waste sites. The investigation includes liquid waste disposal sites with associated structures such as pipelines that were used for discharge of radioactive liquids from processing facilities to the ground (e.g., ponds, cribs, and ditches), burial grounds, the peripheral regions of the single-shell waste storage tank farms where leakage of high-level radioactive waste constituents from specific tanks may have migrated, and unplanned releases. Most of the liquid waste sites and all of the burial grounds and unplanned release sites have been assigned to the Environmental Restoration (ER) Program. A small percentage of the soil waste sites and the peripheral regions of the tank farms have been assigned to the DOE Office of River Protection (DOE-ORP).

The purpose of the Hanford 200 Areas Spectral Gamma Baseline Characterization Project is to present spectral gamma data collected from existing boreholes in and adjacent to waste sites in the Hanford 200 Areas. High-resolution gamma-energy spectra are collected in these boreholes using consistent and defensible methodology. This work effectively extends the existing baseline data set developed for the Hanford single-shell tank farms into the surrounding areas. The baseline data are evaluated to determine the source(s) of the contamination, to develop a dataset that can be used to assess future changes, and to correlate the geophysical signatures of known and presumed geologic features that may affect radionuclide migration within the vadose zone. This information is needed to manage the sites and to make informed decisions about subsequent environmental activities.

The Spectral Gamma Logging System (SGLS) is used to acquire gamma-ray energy spectra from boreholes and wells related to the 200 Area waste sites. Intervals of high gamma-ray intensity are logged with the High Rate Logging System (HRLS).

Gamma spectra from each borehole are analyzed to determine concentrations of naturally occurring radionuclides potassium-40 (^{40}K), thorium-232 (^{232}Th), uranium-238 (^{238}U), and associated decay progeny, as well as, man-made gamma-emitting radionuclides such as cesium-137 (^{137}Cs), cobalt-60 (^{60}Co), and europium-152/154 ($^{152/154}$Eu). Variations in naturally occurring radionuclides are useful in stratigraphic correlation.

This project is limited in scope to passive spectral gamma-ray logging. As a result, only radionuclides that decay with the emission of gamma-ray photons can be detected and quantified. Only existing boreholes/wells and boreholes recently drilled for other projects are logged. No new borehole drilling is specified or planned as a part of this project, although recommendations for additional boreholes may be provided when appropriate. Additional details regarding the scope and general approach to this characterization program are included in the baseline characterization plan (DOE 2001c) and project management plan (DOE 2001b).

Specific activities under this project include preparation and maintenance of a database of existing boreholes and geophysical log data, logging existing boreholes with the SGLS and HRLS, analyses and plotting of log data, and preparation of reports. Because many waste sites are the subjects of site characterization efforts in RI/FS work plans, well logging is performed in existing and new boreholes to support these activities, and data are provided for incorporation into the Remedial Investigation Reports.

1.3 Project Objectives

Specific project objectives are:

- To use passive spectral gamma logging to identify the activities of man-made radionuclide contaminants and to estimate current subsurface radionuclide contamination in the vicinity of 200 Area waste sites. Many areas of the subsurface have been contaminated by the disposal of liquid waste to the ground, and, in some cases, by surface spills.

- To identify probable sources of contamination by measuring the radionuclide contaminant activity in multiple boreholes and correlating data between those boreholes, and to link detected contamination with probable sources.

- To provide a baseline dataset to help assess ongoing migration of the radionuclides through the vadose zone, and to provide data for the validation and/or determination of initial or boundary conditions of contaminant transport models.

- To generate data that can be used for stratigraphic correlations in 200 Area waste sites. Migration of radionuclides through the vadose zone is affected by differences in vadose zone composition, porosity, density, and water content. Accurate stratigraphic characterization helps in identifying target-monitoring horizons and in delineating controlling factors in subsurface flow. Lithologic characterization data include vertical profiles of naturally occurring ^{40}K, ^{238}U, and ^{232}Th.

Although the primary focus of this project is interpretation and evaluation of spectral gamma logs, part of this project involves assessment of existing data, such as historical gross gamma data, spectral gamma and neutron logs, drilling logs, groundwater monitoring information, geology and hydrogeology information, construction details, and operational information. This information is compiled and evaluated with the spectral gamma data to understand its significance in relation to the nature and extent of vadose zone contamination. The background and historical information help to identify potential sources of contamination, the date of contamination, rate of contaminant migration (if it occurs), and to explain the nature of the contamination identified by the spectral gamma log data.

2.0 Spectral Gamma-Ray Logging Methods

The following sections discuss field and technical methods used by the Hanford 200 Areas Spectral Gamma Baseline Characterization Project that have been specifically developed for high-resolution borehole measurements with a sensitivity and accuracy comparable to laboratory equipment.

2.1 Field Methods

Existing boreholes are logged by the SGLS, which uses a cryogenically cooled HPGe detector with an intrinsic efficiency of approximately 35 percent. The HRLS is used in zones of high gamma activity, where the SGLS detector can become "saturated" and no usable spectra can be acquired. Both detector systems are operated on the same logging vehicle. Each combination of sonde and logging vehicle represents a unique logging system. Two logging vehicles, three SGLS sondes, and one HRLS sonde are available. Table 2-1 lists currently available logging systems.

Table 2-1. Logging Sondes and Vehicles (July 2002)

			Vehicle	
Sonde	**Type**	**Serial No.**	**Gamma 1** HO 68B-3574	**Gamma 2** HO 68B-3572
A	SGLS	34TP20893A	N/A[1]	(11/01)[2]
B	SGLS	36TP21095A	N/A	(11/01)
C	HRLS	39A314	(11/02)	N/A
D	SGLS	34TP11019B	(06/01)	N/A

[1] Not applicable
[2] Date of last calibration

SGLS and HRLS log data are collected in accordance with a logging procedure (DOE 2001a). Gamma energy spectra are collected in "move-stop-acquire" mode where the sonde is held stationary for measurement and then moved a specified depth increment to the next measurement point. The typical depth increment is 0.5 ft. System gain is adjusted as necessary to maintain a consistent channel relationship for a marker peak (typically the ^{40}K peak at 1461 keV). Measurement times are selected to detect prominent gamma peaks associated with natural radionuclides (^{40}K, ^{238}U, and ^{232}Th). Depending on casing thickness, typical count times are 100 or 200 seconds (s) for the SGLS and 300 s for the HRLS. This results in logging speeds of feet per hour instead of the feet per minute rates common in the petroleum and mineral industries. In deep boreholes with little or no contamination, a depth increment of 1.0 ft may be used to expedite logging. This larger depth

increment is generally preferable to reducing count time, because the overall spectrum quality is not compromised. Verification spectra are collected at the beginning and end of each logging day to monitor system performance, and repeat sections are logged to demonstrate repeatability and consistency.

2.2 Technical Methods

Evaluation of gamma energy spectra provides identification and quantification of naturally occurring and man-made radionuclides based on the characteristic energy emissions associated with their decay. Only gamma rays of sufficient energy to penetrate the steel borehole casing and sonde housing can be detected by the SGLS or HRLS. Radionuclides that emit one or more gamma rays at energies between about 150 and 2,800 keV are detectable with the SGLS. The minimum detectable concentration is dependent upon detector efficiency at the appropriate energy level, background activity, and the yield (gamma rays emitted, on average, per decay). Factors such as casing, water, shielding, and the presence of other radionuclides also have an effect. Because waste disposal to the soil column has been discontinued, radionuclides with half lives of less than one year have not been detected on the spectral gamma logs and are presumed to have decayed to insignificant levels. Tables 2-2 and 2-3 summarize naturally occurring and man-made radionuclides that can be detected with the SGLS. The terms "primary gamma ray" and "secondary gamma ray" are used to differentiate between the more prominent gamma energy peaks and other, less prominent peaks that may be useful for confirmation. The values indicated in bold are those generally used to calculate concentrations.

Table 2-2. Naturally Occurring Gamma-Emitting Radionuclides

	Primary Gamma Rays			Secondary Gamma Rays		
Radionuclide	**Daughter**	**E (keV)**	**Y (%)**	**Daughter**	**E (keV)**	**Y (%)**
^{40}K		**1460.83**	**10.67**			
^{232}Th	^{212}Pb	238.63	43.30	^{228}Ac	911.21	26.60
	^{208}Tl	**2614.53**	**35.64**	^{228}Ac	968.97	16.17
	^{208}Tl	583.19	30.36	^{228}Ac	338.32	11.25
				^{208}Tl	510.77	8.06
^{238}U[1]	^{214}Bi	**609.31**	**44.79**	^{214}Pb	295.21	18.50
	^{214}Pb	351.92	35.80	^{214}Bi	1120.29	14.80
	^{214}Bi	**1764.49**	**15.36**	^{214}Pb	241.98	7.50
				^{214}Bi	1238.11	5.86
				^{214}Bi	2204.21	4.86
				^{214}Bi	2447.86	1.50

[1] Attainment of secular equilibrium between ^{238}U and $^{214}Bi/^{214}Pb$ requires long time periods on the order of a million years. Activities of both ^{214}Bi and ^{214}Pb are commonly assumed to be equal to the activity of naturally occurring ^{238}U. However, these radionuclides are short-term daughter products of ^{222}Rn, and accumulations of radon gas inside the casing may temporarily elevate the decay activities of $^{214}Bi/^{214}Pb$ relative to the decay activity of ^{238}U.

Table 2-3. Man-Made Radionuclides

Radionuclide	Half Life (Years)	Primary Gamma Rays		Secondary Gamma Rays	
		E (keV)	Y (%)	E (keV)	Y (%)
^{60}Co	5.2714	**1332.50** **1173.24**	**99.98** **99.90**		
^{106}Ru	1.0238	511.86	20.40	621.93	9.93
^{125}Sb	2.7582	**427.88**	**29.60**	600.60 635.95 463.37	17.86 11.31 10.49
^{126}Sn	1.E+5	**414.50**	**86.00**	666.10 694.80	86.00 82.56
^{134}Cs	2.062	604.70	97.56	795.85	85.44
^{137}Cs	30.07	**661.66**	**85.10**		
^{152}Eu	13.542	**1408.01**	**20.87**	121.78 344.28 964.13 1112.12 778.90	28.42 26.58 14.34 13.54 12.96
^{154}Eu	8.593	**1274.44**	**35.19**	123.07 723.31 1004.73 873.19	40.79 20.22 18.01 12.27
^{155}Eu	4.7611	105.31	21.15		
^{235}U	7.038E+08	**185.72**	**57.20**	205.31	5.01
^{234m}Pa (^{238}U[1])	4.47E+09	**1001.03**	**0.84**	811.00 766.36	0.51 0.29
^{237}Np	2.14E+06	312.17	38.60		
^{238}Pu	87.7	99.853	0.0074	43.498	0.04
^{239}Pu	24110	129.30 **375.05** 413.71	0.0063 **0.0016** 0.0015		
^{240}Pu	6563	104.234	0.007	45.244 160.308	0.045 0.0004
^{241}Pu	14.35	148.567	0.0002	103.68	0.0001
^{241}Am	432.2	59.54[2]	35.90	102.98 335.37 368.05 662.40 772.01	0.02 0.0005 0.0002 0.0004 0.0002

[1] ^{234m}Pa is a short-term daughter of ^{238}U. Secular equilibrium is achieved relatively quickly. Because of the relatively low gamma yield, this peak is not observed when only background levels of naturally occurring ^{238}U are present. Hence, the presence of gamma peaks associated with ^{234m}Pa without corresponding peaks associated with ^{214}Pb and ^{214}Bi indicates the presence of chemically processed uranium.

[2] The 59.54-keV gamma ray may not be detectable in thick casing.

Other radionuclides of interest, such as tritium (^{3}H), strontium-90 (^{90}Sr), and technetium-99 (^{99}Tc), are "pure" beta emitters and do not emit any gamma rays that can be detected with the SGLS. However, experience has shown that the presence of ^{90}Sr at concentrations greater than about 1,000 pCi/g can be inferred from the *bremsstrahlung* generated from interaction of the high-energy beta emissions from ^{90}Sr with the steel casing.

Field gamma spectra are processed and analyzed in accordance with a data analysis manual (manual in revision). Conventional gamma spectra analysis software is used to detect gamma energy peaks, identify the source radionuclide, and determine the net count rate, counting error, and minimum detectable activity. From the net count rate (P_n, cps) for a specific energy peak, the apparent concentration of the source radionuclide (C_a, pCi/g) is determined by:

$$C_a = \frac{27.027}{Y} \times I(E) \times DTC \times K_c \times K_w \times K_s \times P_n ,$$

where Y is the radionuclide yield, I(E) is the logging system calibration function, DTC is the dead time correction, and K_c, K_w, and K_s are energy-dependent correction factors for casing, water, and shielding. The calibration function, I(E), is unique for each combination of sonde and logging vehicle. Values of the calibration function are updated annually and documented in calibration certificates and a calibration report (Koizumi 2002). Concentration error and minimum detectable concentration are calculated using similar equations. The reported concentration error is based on only the estimated counting error. No effort is made to include the effects of errors in the calibration function or correction factors. These errors are discussed in the calibration report (Koizumi 2002). The term "apparent concentration" is used because the calibration model is based on an effectively infinite, homogeneous distribution uniformly distributed about the borehole axis.

The minimum detection level (MDL) of a radionuclide represents the lowest concentration at which the positive identification of a gamma-ray peak for that radionuclide is statistically defensible. A description of the MDL calculation is included in the data analysis manual (manual in revision).

For a counting time of 100 s, the MDL for ^{137}Cs is typically about 0.2 pCi/g. The MDL differs slightly for each spectrum depending upon count time, background activity and concentrations of other radionuclides at the data point, as well as casing thickness. In regions of higher man-made radionuclide concentrations, the Compton background continuum becomes elevated, increasing the MDL value.

The MDL for ^{60}Co is about 0.15 pCi/g; the MDL for ^{154}Eu is approximately 0.2 pCi/g; and the MDLs for ^{235}U and ^{238}U are approximately 1 and 10 pCi/g, respectively. These values are typical for a 100-s counting time.

Natural and man-made radionuclide concentrations, total gamma count rate, and dead time are plotted as a function of depth. These plots are included in a Log Data Report that also summarizes borehole construction details, logging conditions, analysis notes, and log plot notes, as well as a brief discussion of results and interpretations. When appropriate, comparison plots with other available logs are also included. Log Data Reports for boreholes in the study area are included in Appendix A on the accompanying CD-ROM.

Log data and geological information from surrounding boreholes are assembled and correlated in an effort to identify contaminated zones and potential sources of contamination. Historical gross gamma, spectral gamma, and neutron log data are incorporated where available. Three-dimensional visualization software is used to interpolate data between boreholes.

In accordance with conventional logging practice, log data are presented in terms of depth relative to a well-defined fixed point, such as top of casing in existing boreholes or wells. Where a fixed reference point is not available, depth relative to ground surface is generally used. In many cases, a

reference elevation may not be available at the time log data are collected. When comparing features between boreholes or in stratigraphic correlation, elevation relative to a common reference datum (typically mean sea level) is used, which provides a better indication of the spatial position of the feature or bed and eliminates confusion resulting when boreholes are located at different ground surface elevations.

A Waste Site Summary Report (WSSR) documents the results of the correlation and evaluation process for each group of waste sites. Waste site groups have been defined in terms of physical proximity and common configuration or operational history. Each WSSR provides a review of background information that includes a description and operational history of the waste sites, a summary of geologic and hydrogeologic conditions, a review of previous investigations, and any existing data such as gross gamma or spectral logs, geologic logs, or groundwater data. An assessment and interpretation of the spectral gamma-ray log information are also provided, along with conclusions and recommendations on future data needs or corrective action, where appropriate.

3.0 Background and Physical Setting of the 216-B-8 Crib and Adjacent Sites

Figure 2 is a map of the B-BX-BY Waste Management Area and vicinity that shows the general location of the major waste sites. A more detailed map of the area is shown in Figure 3. Three major waste sites within the area that have existing boreholes available for evaluation are the 216-B-7A&B Cribs, the 216-B-8 Crib and Tile Field, and the 216-B-11A&B Reverse Wells. Other waste sites that do not have nearby boreholes include the 216-B-51 French Drain; the 241-B-252 Diversion Box, the 241-B-301 Catch Tank associated with the B Tank Farm; and the 244-BX-DCRT (Double Contained Receiving Tank) near the BX Tank Farm. The study area is bounded in the west by the BX and BY Tank Farms and in the south by the B Tank Farm. The north and east boundaries were selected to include deep boreholes in the area that are not generally associated with specific waste sites but are useful to assess possible impacts by the waste sites and to determine potential sources of contamination.

The information in the following sections was obtained from a variety of sources, including Waste Information Data System (WIDS), System Assessment Capability (SAC), Simpson et al. (2001), *B Plant Source Aggregate Area Management Study Report* (DOE 1993a), Brodeur et al. (1993), Wood et al. (2000), and the addenda to the B, BX, and BY Tank Farm Reports (DOE 2000a, 2000b, 2000c).

3.1 Background of the 200 Areas

Established in 1943, the Hanford Site was originally designed, built, and operated to produce plutonium for nuclear weapons. Uranium metal billets were received in the 300 Area and fabricated into jacketed fuel rods. The fuel rods were loaded into graphite-moderated reactors in the 100 Areas. With the exception of 100-N, which also provided steam to the Hanford Generating Project, these reactors were operated for the sole purpose of producing ^{239}Pu from neutron activation of ^{238}U. The fuel rods were then transported to the 200 Areas, where plutonium and uranium were separated from the residual activation and fission products using a variety of liquid chemical separation processes. The 600 Area includes portions of the Hanford Site not included in the 100, 200, or 300 Areas and served primarily as transportation corridors and buffer zones between the fabrication, irradiation, and chemical processing areas (DOE 1998).

Chemical separations process facilities were sited in both the 200 East and 200 West Areas. The 200 North Area temporarily stored irradiated fuel rods, allowing short-lived fission products to decay before being shipped to separations plants. With the startup of the separation plants, high-level wastes containing the bulk of the fission products were discharged to large underground steel tanks, and large quantities of liquid wastes (primarily water) containing minor concentrations of radionuclides and chemicals were discharged to the soil column and percolated into the vadose zone. Depending on contaminant concentrations and a consequent need for isolation, liquid wastes were discharged either to surface ponds and ditches or to underground cribs, reverse wells, trenches, and French drains. These liquid disposal sites were located in the 200 Areas near the processing plants and in the nearby 600 Areas (DOE 1998).

3.2 Geologic Conditions

This section summarizes the geologic setting of the Hanford Site and the northeast surrounding waste sites. Figure 4 shows the general stratigraphy for the B-BX-BY WMA and vicinity. Lithologic information, used to develop stratigraphy, is obtained from field analysis of sediment samples retrieved during borehole drilling operations and from nearby outcrops. When available, gross gamma-ray logs have been used to support the geologic interpretation. Most of the boreholes were drilled with a cable tool drill rig, and the samples were obtained from bailings, core barrels, or as retained cuttings, generally from 5-ft intervals. Lindsey and Law (1993), Lindsey et al. (1994), and Wood et al. (2000) presented detailed descriptions and interpretations of the geologic formations near and within the B-BX-BY WMA.

3.2.1 Stratigraphy

Overlying the basalt flows of the Columbia River Basalt Group are the Ringold Formation, the unnamed Plio-Pleistocene unit, the informal Hanford formation, and Holocene-Age deposits. Rockwell (1979), Reidel et al. (1992), Delaney et al. (1991), Lindsey (1991), Lindsey et al. (1994), and Bjornstad et al. (2002) (draft report) have presented extensive descriptions and discussions of these formations. Bjornstad et al. (2002) currently are formalizing the stratigraphic nomenclature for post-Ringold sediments at the Hanford Site. When the nomenclature proposed by Bjornstad et al. (2002) is finalized, it will be used in subsequent reports.

3.2.1.1 Columbia River Basalt Group

The Columbia River Basalt Group is comprised of 174,000 km^3 of tholeiitic flood-basalt flows that erupted between 17 and 6 million years ago and cover approximately 164,000 km^2 of eastern Washington, Oregon, and western Idaho (Reidel et al. 1989). The distribution of the basalt flows reflects the tectonic history of the area (Reidel et al. 1989). The basalt is as much as 4,000 m thick in the vicinity of the Hanford Site (Reidel et al. 1989; Glover 1985). The uppermost basalt flow, the Elephant Mountain Member, is at an elevation of about 390 ft under the waste sites. Reidel et al. (1989), Reidel and Fecht (1981), and Rockwell (1979) presented additional information about the Columbia River Basalt Group.

3.2.1.2 Ringold Formation

Ringold sediments are predominantly comprised of layers of fluvial sand, ancient soils (paleosols), and lacustrine sand, silt, and clay (Lindsey 1996). This formation may be as much as 600 ft thick across the Hanford Site. It is comprised of uncemented to locally well-cemented clay, silt, fine- to coarse-grained sand, and pebble to cobble conglomerate. Ringold sediments are absent underneath the study area (Williams et al. 2000).

3.2.1.3 Plio-Pleistocene Sediments

The Plio-Pleistocene unit sediments unconformably overlie the Ringold Formation. This unit is laterally discontinuous. Plio-Pleistocene sediments, which are absent in the vicinity of the study area (Williams et al. 2000), are comprised of locally derived basaltic alluvium and pedogenic calcium-carbonate-rich material. The basaltic material is comprised of weathered and unweathered locally derived basaltic gravel containing varying amounts of sand and silt. The carbonate-rich sediments are comprised of calcium carbonate cemented silt, sand, and gravel interfingering with carbonate-poor sediments. Both of these facies may be present at some locations. The Plio-Pleistocene unit generally dips to the south-southwest. Bjornstad et al. (2002) have proposed naming these sediments the Cold Creek Interval.

In the past, the Plio-Pleistocene was divided into an upper silty sand to sandy silt that was designated as early Palouse soil and a lower calcium carbonate-rich interval often referred to as the "caliche layer" (Lindsey et al. 2000). Numerous investigations conducted in the 1990s have observed that the upper unit contains stratified fine sand indicative of lacustrine deposition and not eolian conditions associated with the early Palouse soil (Lindsey et al. 2000). The Plio-Pleistocene unit also contains a series of paleosols with calcium carbonate development indicative of an arid environment (Slate 1996).

The pre-Missoula gravel is comprised of quartzose to gneissic clast-supported pebble to cobble gravel with quartzo-feldspathic sand matrix that underlies the Hanford formation in the east-central region of the Cold Creek syncline and at the east end of Gable Mountain anticline east and south of the 200 East Area (Williams et al. 2000).

A compact, massive loess-like silt with minor fine-grained sand unit may overlie the Plio-Pleistocene unit. This unit is designated the "Early Palouse soil," and it can range to tens of feet thick. The Early Palouse sediments can grade upward into sediments similar to those at the base of the overlying Hanford formation, making the contact between these two lithologic units difficult to distinguish. The Early Palouse soil is thickest in the southwest and southeast portions of the 200 West Area, where it reaches a maximum thickness of 65 ft. The Early Palouse soil is not present underneath the surrounding waste sites (Williams et al. 2000).

3.2.1.4 Hanford Formation

A series of Pleistocene catastrophic flood deposits, informally known as the Hanford formation, overlies the Plio-Pleistocene and older sediments throughout the Hanford Site. The Hanford formation is comprised of gravel, sand, and silt. The sediments of the Hanford formation are unconsolidated, uncemented, and highly transmissive for the flow of water. This formation is thickest in the central Hanford Site, where it thickens to 350 ft. The Hanford formation is divided into three facies (gravel-dominated, sand-dominated, and silt-dominated) that are gradational with each other. Bjornstad et al. (2002), Lindsey (1991), Reidel et al. (1992), and Wood et al. (2000) provided detailed discussions of the Hanford formation lithology. The Hanford Site is in the process of formalizing the stratigraphic nomenclature for the Hanford formation (Bjornstad et al. 2002).

Interpretations of sediment samples obtained from boreholes in the 200 Areas (Lindsey and Law 1993; Lindsey et al. 1994; and Reidel et al. 1992) have resulted in subdividing the Hanford formation into units (H1a, H1, H2, H2a, H3, and H4). Units H1a, H2a, H3, and H4 are laterally discontinuous, and H3 and H4 are locally identified at the base of the formation (Lindsey et al. 2000). These interpretations have placed the contact between the upper Hanford unit H1 and the intermediate Hanford unit H2 at an elevation of about 615 ft in the area. The Hanford H3 occurs at an approximate elevation of about 430 ft underneath the waste sites. Hanford H4 is absent.

The rhythmite facies sediments (Hanford H4) were deposited under slack water conditions and in back-flooded areas remote from the main flood channel. These sediments are comprised of thinly bedded, plane-laminated and ripple cross-laminated silt and fine- to coarse-grained sand and commonly display normally graded rhythmites a few centimeters to several tens of centimeters thick (Baker et al. 1991; DOE 1988). This facies dominates the Hanford formation along the western, southern, and northern margins of the Pasco Basin, within and south of the 200 Areas.

The Hanford H3 unit varies from 30 to 50 ft thick, and this lower coarse-grained unit is comprised of pebble and cobble gravel with interbedded sand. The H3 generally consists of coarse-grained basaltic sand and granule to boulder gravel, and ranges from well sorted to poorly sorted. In outcrop, these sediments display massive bedding, planar to low-angle bedding, and large-scale planar cross bedding. The gravel-dominated facies was deposited by high-energy floodwaters in or immediately adjacent to the main flood channel.

The Hanford H2 unit is about 180 to 190 ft thick in the area and is comprised of sand-dominated facies with interbedded silt lenses (Lindsay and Law 1993; Lindsey et al. 1994). Some laterally discontinuous silt-rich interbeds are reported in this area, and these high-silt content zones may have higher moisture content and $CaCO_3$ content than the surrounding sand-dominated material. The depositional facies are discontinuous in both horizontal and vertical extents, and little correlation

between boreholes has been possible in terms of the minor differences between such features as the silty sand and sandy silt layers (Lindsay and Law 1993; Lindsey et al. 1994).

Unit H1 is dominated by coarse to granule sand and lesser pebble gravel formed from a complex interfingering of gravel and sand-dominated facies (Lindsay and Law 1993; Lindsey et al. 1994). The relative abundance of gravelly facies decreases from the northwest to the south. As gravel content decreases, unit H1 interfingers with the more sand-rich strata of unit H2.

Clastic dikes comprised of layers of silt, sand, and granule gravel crosscut the Hanford formation. These clastic dikes generally crosscut the bedding as alternating vertical to subvertical dikes, although they may locally run parallel to bedding. Clastic dikes also occur in the older sediments (Fecht et al. 1999).

3.2.1.5 Holocene Surficial Deposits

Holocene surficial deposits are comprised of a mix of silt, sand, and gravel deposited by a combination of eolian and alluvial processes (DOE 1988).

3.2.2 Structure

The Hanford Site is located in the Pasco Basin, which is a physical and structural depression in the Columbia Plateau created by tectonic activity and folding of the Columbia River basalts. The structural framework of the Pasco Basin began developing before Columbia River Basalt Group volcanism (Reidel et al. 1994) and was an area of subsidence that accumulated thick deposits of sediments and volcanic rock. This pattern continued through Columbia River Basalt Group volcanism. Anticlinal ridges were growing under north-south compression. This compression resulted in a series of anticlinal ridges and synclinal valleys with a general east-west trend. The north-south compression and east-west extension have persisted from at least the middle Miocene to the present (Hooper and Camp 1981; Reidel 1984; Hooper and Conrey 1989; Reidel et al. 1989).

The geologic structure of the Pasco Basin area is dominated by a series of east-west-trending anticlines and synclines. Anticlines to the north and south create topographic high areas (Gable Mountain and Rattlesnake Mountain, respectively) with outcropping basalt flows. The Hanford Site 200 Areas are situated on the northern limb of the Cold Creek syncline where bedrock dips to the south at an angle of approximately 5 degrees. Approximately 270 ft of sediments overlie the dipping basalt bedrock in the vicinity of the site.

3.3 Hydrology

Hartman (1999), Narbutovskih (1998), and Narbutovskih (2000) described the hydrology of the Hanford Site and the B-BX-BY WMA. Considerable uncertainty currently exists regarding both velocity and direction of groundwater flow in certain regions of the 200 East Area in the vicinity of the B-BX-BY WMA. The water table is nearly flat with a maximum of 7-in. change in groundwater elevations across the WMA (Narbutovskih 2000). The groundwater level has been declining since liquid discharges were curtailed in the 1980s. The top of the unconfined aquifer is currently at an elevation of 401 ft (122.2 m) and within the H3 unit. The base of the unconfined aquifer is believed to be the top of the basalt. Aquifer thickness is approximately 12 ft in the area. The study area is located in a region of very low hydraulic gradient between the groundwater mound beneath B Pond, which is located east of the 200 East Area and the eastward-moving groundwater from the 200 West Area (Caggiano 1996).

In June 1996, an assessment groundwater monitoring program was initiated for WMA B-BX-BY when elevated specific conductance was measured in groundwater monitoring well 299-E33-32, west of the WMA. Elevated specific conductance resulted from increases in nitrate, chloride, sulfate, and sodium concentrations. The June 1996 sample confirmed elevated specific conductance that was initially measured in the February 1996 sampling of the monitoring well. During an expanded Phase I investigation, elevated conductivity was also observed in the February 1997 sample for downgradient well 299-E33-41, which is in the southwest portion of the study area, east of the BX Tank Farm. Increases in nitrate, chloride, sulfate, and sodium were the cause of the elevated conductivity (Narbutovskih 1998). ^{99}Tc, a non-RCRA co-contaminant, was also identified above previously measured concentrations in the well samples. Northeast of the WMA, significant ^{99}Tc concentrations were detected in wells 299-E33-16 and -18, but very little in wells 299-E33-15, -17, -20, and -39 (Narbutovskih 2000). Uranium had also increased in concentration in well 299-E33-41 by March 1998. Elevated uranium has also been detected in wells 299-E33-13 and -18. ^{60}Co has been detected near its quantitation limit (20.49 pCi/L) in wells 299-E33-13 and -16. Although assessment wells are monitored for ^{137}Cs and ^{90}Sr, there are currently no known occurrences in the groundwater (Narbutovskih 2000).

3.4 Description of the 216-B-8 Crib and Adjacent Sites

Several facilities into which millions of gallons of liquid waste and wastewater were discharged to the soil column are located in this study area. Major waste sites include the 216-B-7A&B Cribs, 216-B-8 Crib and associated Tile Field, and the 216-B-11A&B Reverse Wells. Other facilities that may have minor impacts to the vadose zone include the 216-B-51 French Drain, 241-B-252 Diversion Box, 241-B-301 Catch Tank, and the 244-BX-DCRT located in the southwest portion of the study area. A facility adjacent to the 241-B-8 Crib known as the Health Instrument Shaft was used to monitor the crib but did not receive effluent. Unplanned Releases (UPRs) designated 200-E-121, -231, -144 also occurred within the area. The boreholes characterized included deep boreholes and/or groundwater monitoring wells in the vicinity of the waste sites and the first row of tanks from the tank farms. A brief discussion of each site or unplanned release is included in the following sections. Figure 3 provides the locations of each site.

The 216-B-7A&B Cribs are located approximately 50 ft north of the B Tank Farm. Figures 5a and 5b show views of the area overlying the 216-B-7A Crib and associated boreholes. Note: Physical inspection of the site suggests the coordinates provided in the WIDS database for the -7A Crib may

be incorrect. The location of the crib was adjusted about 20 ft to the northwest on the base map in Figure 3 to reflect the proper location. The 216-B-7A&B Cribs consist of two wooden structures, placed side by side, connected by underground piping. The two cribs are located about 20 ft apart and are in line with a 3-in. steel inlet pipe that supplied waste to both cribs simultaneously. Each crib is a 12-ft by 12-ft by 4-ft wooden structure made of 6-in. by 6-in. timbers, placed in a 14-ft by 14-ft by 14-ft deep excavation. Each crib is a hollow structure, (i.e, not backfilled with gravel [DOE 1993a]).

Effluent drained into the 216-B-7A&7B Cribs simultaneously through a T-fitting in the pipeline from the 201-B settling tanks (241-B-201, 241-B-202, 241-B-203, and 241-B-204) located inside the B Tank Farm. Process effluent from 221-B and 224-B was routed to the settling tanks from 1946 through 1967 and dispersed to the cribs. In 1951, cell drainage from 221-B was diverted to the 216-B-9 Crib. In 1954, the 224-B waste stream was diverted to the 216-B-8 Crib when the cribs exceeded their infiltration capacity. The cribs were reactivated and used intermittently from December 1954 through May 1967 when it was determined that they had reached their radionuclide disposal capacity (WIDS).

The cribs are located beneath a larger area of contaminated soil from the UPR-200-E-144 stabilization. The contaminated soil from the unplanned release area and the cribs was covered with clean backfill and posted with "Underground Radioactive Material" signs. The crib locations are identified with light steel posts and chain with signs indicating "Cave-in Potential".

The 216-B-8 Crib and Tile Field is an inactive waste management unit located about 350 ft north of the B Tank Farm. Figures 6a and 6b show the area of the crib and a portion of the tile field and associated boreholes. The crib is a 12-ft by 12-ft wooden structure in a 14-ft by 14-ft by 22.5-ft deep excavation. The structure is hollow and not gravel filled. The tile field is 300 ft long, 100 ft wide, and fed by a 12-in. vitrified clay pipe (VCP) trunk with eight pipes branching at 45 degrees. The piping is placed over 4 ft of gravel with 6 in. of gravel above the piping. The bottom of the tile field excavation is 4 ft below grade and the sides of the excavation are sloped at a ratio of 1:1.5. Piping connected the unit to the B-110, -111, and -112 single-shell tanks in the B Tank Farm. The crib was tied directly to waste lines, bypassing the 241-B-361 settling tank, and sludge accumulated in the crib, decreasing its capacity. The tile field was then placed into service to receive the waste overflow from the crib.

The Health Instrument Shaft (WIDS Sitecode 200-E-45) is located adjacent to the west side of the 216-B-8 Crib. The Health Instrument Shaft was originally installed to allow Health Instrument technicians to descend a ladder and collect liquid and soil samples from a depth of approximately 10 ft and 20 ft below the bottom of the 216-B-8 Crib through openings in the shaft. Perforated lateral pipes extending beneath the crib allowed liquid waste from the crib to enter the pipes and collect in sample cups. Other holes were made in the side of the shaft facing the crib to collect sediment samples. Samples were collected for several years until December 31, 1949.

In August 1948, sludge from tank B-104 was inadvertently jetted to the 216-B-8 Crib. Liquid samples collected in the Health Instrument Shaft prior to the sludge discharge contained less than 1,000 disintegrations per minute per liter of alpha contamination. Liquid samples collected after the sludge release contained an average of 17,500 disintegrations per minute per liter of alpha contamination.

Sediment samples collected from approximately 18 ft below the crib through the Health Instrument Shaft prior to the sludge release contained beta-gamma activity of 0.13 microcuries per kilogram. After the sludge release the activity increased to 0.33 microcuries per kilogram. No alpha contamination was identified in the sediment samples.

Citric and hydrochloric acids were added to the crib to help clear the sludge from the crib. The tile field was built to receive overflow from the plugged crib because the acids did not significantly reduce the sludge. A sudden decrease in the crib capacity led to the discovery of approximately 15 in. of sludge in the crib. Some sludge washed to at least 20 ft below the crib bottom and was collected in the Health Instrument Shaft sample cups. The plutonium activity in the sludge samples was 900 microcuries per kilogram of sludge, 1,000 times higher than the plutonium content of the supernate liquid usually discharged to cribs. The fission product activity in the sludge samples was 9,000 microcuries per kilogram of sludge, roughly 5,000 times greater than the fission product activity in supernate liquid (WIDS).

In 1949, radiological readings as much as 4 rad/hour were recorded at the bottom of the shaft. As of December 1949, 105 liquid samples, four sludge samples, and seven sediment samples had been collected and analyzed to characterize the operation of the 216-B-8 Crib. Liquid samples collected at the 10-ft level and the 20-ft level both contained an average of 0.5 microcuries per liter.

The shaft structure was later filled with water and used to test contaminated tank farm pumps. The last known pump test was performed in 1973.

The 216-B-11A&B Reverse Wells (Figure 7) are located approximately 250 ft north of the B Tank Farm. These two wells are placed about 60 ft apart in line with a 3-in. steel inlet pipe. Each well consists of 2-ft-diameter by 30-ft-long corrugated steel culvert buried vertically, 10 ft below the ground surface to a total depth of 40 ft below ground surface. The culverts are perforated on 6-in. centers at 12-in. vertical intervals and placed in an 8-ft-diameter excavation that is filled with 3-in.-diameter rock. The reverse wells were deactivated when it became evident that cribs and trenches were a more effective means of waste disposal. The site was deactivated by blanking the effluent pipeline in the 242-B Building.

The 216-B-51 French Drain is an inactive waste management unit located about 750 ft north of the B Tank Farm. This unit is comprised of vertically stacked sections of 5-ft-diameter concrete pipe filled with gravel. The bottom of the unit is 14 ft below grade. The French drain received drainage from the pipeline that transferred tri-butyl phosphate waste from the BY Tank Farm to the BC Cribs and Trenches. The drain was active from January 1956 to January 1958.

The 241-B-252 Diversion Box transferred waste solutions from processing and decontamination operations between 1945 and June 1984. This unit is connected to the 241-BX-154 and 241-B-152 Diversion Boxes and the B and BY Tank Farms. The box consists of a 2-ft-thick, walled, reinforced concrete structure with dimensions of 36-ft length by 9-ft width by 15.27-ft depth. Twenty-four 3-in. Hanford-type nozzles are housed inside. The top of the box is a concrete cover block that extends a few inches above grade. Diversion boxes and receiving vaults drain to catch tanks or single-shell tanks. This unit has been isolated (1985) and weather covered.

The 241-B-301 Catch Tank is located approximately 30 ft south of the 241-B-252 Diversion Box. The tank collected waste spilled in the 241-B-151, 241-B-152, 241-B-153, and 241-B-252 Diversion

Boxes during waste transfers. It was in service from 1945 until 1984. Its contents are unknown and it was isolated in 1985 (DOE 1993a).

The 244-BX DCRT is an active waste management unit located in the east side of the BX Tank Farm. The unit last received waste from the BY-102 and -109 (BY Tank Farm) single-shell tanks during the 1991 stabilization campaign (DOE 1993a). The 244-BX-DCRT is constructed of carbon steel with a 117,335 liters (31,000 gallons) design capacity. The tank sets lengthwise in a reinforced concrete, steel-lined vault. The lowest portion of the vault that houses the tank is about 28 ft below grade. The upper portion of the vault is comprised of three sections; the pump pit in the southern section constitutes almost half the space. The filter pit is in the middle section and the instrumentation pit is in the northern section of this part of the vault. The length and diameter values listed in the dimensions section are for the 244-BX Receiver Tank. The concrete vault housing the tank is slightly larger than the tank dimensions.

The Unplanned Release Report UPR-200-E-121 site is a long, narrow area along the east side of Baltimore Avenue. Contaminated soil was apparently removed from this area and placed on top of the 216-B-7A&B Cribs and 216-B-11A&B Reverse Wells. The contaminated soil was covered with clean dirt and reposted with "Underground Radioactive Material" signs.

The explanations in WIDS for the UPR-200-E-144 and the 200-E-231 sites are not clear. Contamination associated with them is considered to be minor.

3.5 Operational History

The B-BX-BY tank farm complex has received waste generated by a variety of major chemical processing operations. Wood et al. (2000) provided a discussion of the operations and wastes transferred to selected waste sites in the study area. Table 3-1 provides a general summary of the sites and associated wastes and Table 3-2 presents an estimate of releases of various radionuclides.

Table 3-1. Summary of the Operational History for the 216-B-8 Crib and Adjacent Waste Sites

Site	Time in Use	Mean Estimate of Volume (m^3)	Source	Type of Waste
216-B-7A Crib	10/1946 - 05/1967	43,400	224-B	224-B facility wastes, 5-6, decon waste
216-B-7B Crib	10/1946 - 05/1967			
216-B-8 Crib and Tile Field	04/1945 - 12/1951	27,200	221-B, 224-B	2C, 5-6, decon waste, 1C condensate
216-B-51 French Drain	01/1956 - 01/1958	0.9	Flush drainage from BC Crib pipeline	Scavenged TBP waste DOE (1993)
216-B-11A&B Reverse Wells	12/1951 - 12/1954	29,600	242-B Evaporator	1C condensate, laboratory waste
References:	DOE (1993a)	Bergeron et al. (2001)	Waite (1991)	Waite (1991)

Table 3-2. Summary of Median Radionuclide Release Estimates for the 216-B-8 Crib and Adjacent Waste Sites

Trench	^{137}Cs (Median Estimate in Curies)	^{154}Eu (Median Estimate in Curies)	^{60}Co (Median Estimate in Curies)	U (total) (Median Estimate in kg)	^{90}Sr (Median Estimate in Curies)	^{99}Tc (Median Estimate in Curies)	^{239}Pu (Median Estimate in Curies)
216-B-7A&B Cribs	8500	0.375	0.02	2750	6210	0.51	2.48
216-B-8 Crib and Tile Field	5370	0.24	0.02	1730	3960	0.32	1.57
216-B-51 French Drain	0.22	0.0012	3.90E-08	0.00002	0.02	0.0048	0.0005
216-B-11A&B Reverse Wells	18	N/A[1]	N/A	.01	1.9	.007	0.248
Reference:	Simpson et al. (2001). Radionuclides are decayed to January 1, 1994.						

[1] N/A – not applicable

3.6 Previous Investigations

A review and visual comparison of gross gamma log profiles conducted over time have been useful to determine on the basis of gamma- ray count rates, if radioactive contamination has changed. Due to the poor spatial resolution of the data (1 ft) and depth registration errors, tabulation of the maximum spatial peak count rates and comparison of those count rates over time are not recommended. Small changes in the position of the borehole probe between loggings cause large variations in the spatial peak count rates. Only by qualitatively reviewing changing trends in the temporal data is it possible to identify actual changes in the formation contamination concentration. The frequency of gross gamma logging is variable in boreholes such that a statistical analysis of trends is not possible.

Previous investigators have provided general assessments of the three major waste sites (216-B-7A&B Cribs, 216-B-8 Crib and Tile Field, and the 216-B-11A&B Reverse Wells) where relatively closely spaced boreholes have been drilled to shallow depths. Other boreholes (299-E33-11 to -20 and -39, -41, and -44) have been drilled to about 260 ft to assess the deep vadose zone and/or the groundwater.

Geophysical logging of monitoring wells and boreholes was conducted as early as 1957 at the facilities related to B Plant operations. Several subsequent evaluations of the log data were performed, including Raymond and McGhan (1964) and Fecht et al. (1977), which are described in this section. DOE (1993a) provided comprehensive descriptions of these studies, a discussion of gross gamma logging methodology, and interpretations of the data. DOE (1993a) also presented an evaluation of individual waste units such as cribs, ponds, trenches, and ditches. Brodeur et al. (1993) provided summaries of several waste units that included waste discharge histories, plan views of the sites, and geophysical log data acquired in the monitoring boreholes.

Raymond and McGhan (1964) provided gross gamma logs from a scintillation detector in "representative wells adjacent to waste disposal sites. Logs of wells that show no ground

contamination are not included." The scintillation detector system had a lower detection limit reported as about 3 pCi/cc (^{106}Ru - ^{106}Rh). Log data between 1957 and 1974 were acquired with a similar detection system but with at least three modifications. These modifications generally were to improve system sensitivity and to reduce noise. The profile of the gamma count rate is not changed significantly by these modifications, so that comparisons over time may be made. Recorder chart data may have been transferred to logarithmic graph paper to account for required scale changes needed to accommodate wide variations in gamma activity encountered during logging, which made direct observation and interpretation somewhat difficult.

Borehole logs acquired in 1959 and 1963 in 299-E33-16 were included as representative of the 216-B-8 Crib and Tile Field (Raymond and McGhan 1964). Both logs "indicate that most of the soil column is highly contaminated." Logs were also acquired in 1959 and 1963 from borehole 299-E33-20, which is located in close proximity to the 216-B-11A Reverse Well. Raymond and McGhan (1964) reported "The 1959 scintillation log shows low level contamination of the entire soil column. The sharp peak noted on both logs at about 80 ft is probably caused by waste from the adjacent 216-B-9 (sic) Crib. The 1963 trace indicates that decay has reduced the radioactivity in most of the soil column to near background level." Only one log acquired in 1963 is reported for borehole 299-E33-60, which is in the vicinity of the 216-B-7A Crib. The log "shows a zone of ground contamination from about 15 to 75 feet below ground surface."

Fecht et al. (1977) evaluated the historical gross gamma-ray logs acquired between 1954 and 1973 and compared these logs to data collected in 1976 with a new logging system. The original equipment was replaced in 1974 with a system that increased the lower limit sensitivity by approximately a factor of three over the former system (Fecht et al. 1977). Data were normalized to adjust the background level of the pre-1976 logs to the 1976 values to allow easier, "direct" comparison of the various logs.

Fecht et al. (1977) evaluated boreholes 299-E33-16, -66, -67, -68, -69, -70, -71, -72, and -89, which are associated with the 216-B-8 Crib. Boreholes 299-E33-15, -73, -74, and -76, associated with the 216-B-8 Tile Field, were also evaluated. A major zone of contamination was found to exist from near the crib bottom to about 93 ft (23.8 m). It was concluded that no measurable migration of radionuclides had occurred beneath the crib or tile field and that no breakthrough of contaminants to the groundwater had occurred. This conclusion may be in conflict with the assessment by Raymond and McGhan (1964) that borehole 299-E33-16, which extends to groundwater, indicated "contamination in most of the borehole."

Boreholes 299-E33-58, -59, -60, -75, and -18 are used to monitor the 216-B-7A&B Cribs. A major zone of contamination was detected between 15 (4.6 m) and 72 ft (21.9 m) in depth. It was concluded that no measurable migration of radionuclides beneath the cribs occurred and that no breakthrough of contaminants to the groundwater had occurred.

Boreholes 299-E33-19 and -20 are used to monitor the vadose zone at the 216-B-11B and -11A Reverse Wells, respectively. Fecht et al. (1977) reported contamination at 90 and 75 ft in boreholes -19 and -20. It was concluded no measurable migration of radionuclides or breakthrough of contaminants to the groundwater had occurred. Raymond and McGhan (1964) reported low-level contamination existed throughout borehole 299-E33-20 in 1959.

Fecht et al. (1977) evaluated the 216-B-51 French Drain on the basis of boreholes 299-E33-11 and -14, which are located approximately 138 ft northeast and 416 ft southeast, respectively, from the site. Background activity was observed in both boreholes and it was concluded that no breakthrough of contaminants to the groundwater had occurred. Raymond and McGhan (1964) did not consider this site.

Boreholes were logged in 1992 using Westinghouse Hanford Corporation's (WHC's) Radionuclide Logging System (RLS) and the Pacific Northwest National Laboratory (PNNL) gross gamma logging system (Brodeur et al. 1993). Data were acquired in boreholes near the 216-B-7A&B Cribs, 216-B-11A&B Reverse Wells, and the 216-B-51 French Drain. Borehole 299-E33-58 was logged with the RLS near the 216-B-7A&B Cribs. In addition, gross gamma logs were collected by PNNL in boreholes 299-E33-58 and -18. The findings that contamination existed to about 100 ft below the cribs were similar to the results of previous investigations. Brodeur noted that although there were no obvious contamination zones in borehole 299-E33-18, the groundwater was contaminated. It was suggested the groundwater contamination was probably from the nearby 216-B-8 Crib or the B Tank Farm.

Borehole 299-E33-20, adjacent to the 21-B-11A Reverse Well, was logged with both the PNNL gross gamma logging system and the RLS (Brodeur et al. 1993). The logs indicated three minor zones of ^{137}Cs contamination at about 10, 90, and 190 ft. On the basis of older gross gamma-ray logs, it was "assumed groundwater at this site had been contaminated with ^{137}Cs released from the reverse well."

Borehole 299-E33-14 was selected for logging with the PNNL gross gamma system and the RLS to evaluate the 216-B-51 French Drain; this borehole is located approximately 416 ft southeast of the site. ^{60}Co was detected between 210 and 228 ft in depth. The contamination was attributed to the 216-B-8 Crib or the B Tank Farm and it was considered unlikely that the French drain contributed to the groundwater contamination (Brodeur et al. 1993).

4.0 SGLS Logging Results

This section details the results of SGLS logging in boreholes within the study area. Log plots and Log Data Reports for these boreholes (Appendix A on accompanying CD-ROM) were previously released and are available on the Internet at **http://www.gjo.doe.gov/programs/hanf/HTFVZ.html**.

4.1 Boreholes and Wells Logged

Nineteen vadose zone boreholes, 10 non-RCRA compliant groundwater monitoring wells, and 3 RCRA-compliant groundwater monitoring wells were logged with the SGLS. Table 4-1 lists the boreholes and groundwater wells that were logged with the SGLS during this investigation. The boreholes and wells used in the vadose zone characterization efforts for the study area are also shown in Figure 3. Three-dimensional sphere plots, which are presented in Figures 8 through 15, provide an enhanced perspective of the contaminant distribution of ^{137}Cs, ^{60}Co, and ^{238}U; ^{235}U is not plotted because it co-exists with ^{238}U. ^{154}Eu was detected only in one borehole in the entire study area (characterization borehole C-3103); a sphere plot is not included for this radionuclide. The sphere plots show the 0.5-ft assays recorded by the SGLS as spheres that are colored and sized to show the position and relative concentrations of each radionuclide. Figures 8 through 10 show the

^{137}Cs, ^{60}Co, and ^{238}U data, respectively, for the 216-B-7A&B Cribs and 216-B-11A&B Reverse Wells. Figures 11 and 12 show the ^{137}Cs and ^{60}Co distribution, respectively, for the 216-B-8 Crib and Tile Field, and Figures 13 through 15 show each radionuclide for the entire study area. Cross sections that include most of these boreholes are discussed in Section 5.0, "Interpretation of Results."

The boreholes and groundwater wells identified in Table 4-1 have been associated with specific liquid waste disposal sites based on their relative proximity to a site. Groundwater wells that are not in close proximity to a waste site are grouped separately. Also included in the table are the dates the boreholes were drilled, previous logs reviewed for this characterization, the depth intervals (elevation) logged with the SGLS, and a general description of the depths at which specific radionuclides were detected. All boreholes were logged from ground surface to the total depth except for three RCRA groundwater wells. The entire lengths of these boreholes were not logged because well construction materials and completion methods precluded accurate measurements, and in the case of 299-E33-44, the logging sonde was temporarily lost in the borehole before logging was completed; the sonde has since been recovered.

Table 4-1. Boreholes and Groundwater Monitoring Wells Logged with the SGLS and HRLS During the Investigation of the 216-B-8 Crib and Adjacent Sites

Borehole	Date Drilled	Previous Logging Review	SGLS Depth Interval Logged (Elevation, ft)	Elevation (ft) Radionuclides Detected	Maximum Concentration (pCi/g)
216-B-7A&B Cribs					
299-E33-18	Feb. 1950	[a]1959, [a]1963, [b]1976, [c]1992, [c]1997	652-381	652-645 - ^{137}Cs 421-401 - $^{235/238}$U 422-410 - ^{60}Co 403-394 - ^{60}Co	2 50/600 2 < 1
299-E33-58	May 1947	[a]1963, [b]1976, [c]1992	653-508	652-642 - ^{137}Cs 633-565 - ^{137}Cs 560-550 - ^{137}Cs	10 4,000 3
299-E33-59	May 1947	[a]1963	653-524	652-641 - ^{137}Cs 622-593 - ^{137}Cs 612-600 - $^{235/238}$U	13 970 3/32
299-E33-60	May 1947	[a]1963	652-497	649-645 - ^{137}Cs 630-573 - ^{137}Cs	10 4,000
C-3103	Sept. 2001	None	651-435	651-638 - ^{137}Cs 637-591 - ^{137}Cs 637-635 - ^{154}Eu	40 200,000 30
299-E33-75	Jan. 1948	[a]1963, [b]1976	652-500	650-636 - ^{137}Cs 623-597 - ^{137}Cs	100 10,000
216-B-11A&B Reverse Wells					
299-E33-19	June 1956	[a]1959	649-405	649-639 - ^{137}Cs 548-545 - ^{137}Cs 421-406 - ^{137}Cs 539-535 - ^{60}Co 522-521 - ^{60}Co 424-420 - ^{60}Co 408-405 - ^{60}Co	65 10 3 < 1 < 1 < 1 < 1

Table 4-1. Boreholes and Groundwater Monitoring Wells Logged with the SGLS and HRLS During the Investigation of the 216-B-8 Crib and Adjacent Sites

Borehole	Date Drilled	Previous Logging Review	SGLS Depth Interval Logged (Elevation, ft)	Elevation (ft) Radionuclides Detected	Maximum Concentration (pCi/g)
299-E33-20	July 1956	[a]1959, [a]1963, [b]1976, [c]1992	650-402	649-632 - ^{137}Cs 564-560 - ^{137}Cs 464-453 - ^{137}Cs (intermittent) 410-407 - ^{137}Cs 405-402 - ^{60}Co	36 40 21 2 < 1
216-B-8 Crib and Tile Field					
299-E33-72	Dec. 1947	[b]1976	642-495	642-639 - ^{137}Cs	14
299-E33-69	Dec. 1947	[a]1963, [b]1976	640-493	640-635 - ^{137}Cs 618-528 - ^{137}Cs	55 50,000
299-E33-89	Dec. 1947	[a]1963, [b]1976	641-495	641-634 - ^{137}Cs 622-495 - ^{137}Cs	55 40,000
299-E33-67	Dec. 1947	[a]1963, [b]1976	641-491	641-635 - ^{137}Cs 618-516 - ^{137}Cs	130 150,000
299-E33-70	Dec. 1947	[a]1963, [b]1976	641-493	641-636 - ^{137}Cs 616-523 - ^{137}Cs	95 50,000
299-E33-68	Dec. 1947	[a]1963, [b]1976	641-494	641-636 - ^{137}Cs 616-528 - ^{137}Cs	200 34,000
299-E33-66	Nov. 1947	[a]1963, [b]1976	641-499	641-637 - ^{137}Cs 636-620 - ^{137}Cs 619-499 - ^{137}Cs	90 < 1 31,000
299-E33-16	Jan. 1953	[a]1963, [a]1968 [b]1976, [c]1992	640-384	640-636 - ^{137}Cs 620-465 - ^{137}Cs 451-430 - ^{137}Cs 425-419 - ^{60}Co 404-389 - ^{60}Co	110 10,000 2 < 1 6
299-E33-71	Dec. 1947	[a]1963, [b]1976	641-633	641-633 - ^{137}Cs 615-529 - ^{137}Cs	180 20,000
299-E33-79	Oct. 1948	none	635-624	632-624 - ^{137}Cs	< 1
299-E33-73	Jan. 1948	[a]1963, [b]1976	633-488	633-629 - ^{137}Cs 615-577 - ^{137}Cs 553-546 - ^{137}Cs	300 1400 < 1
299-E33-74	Jan. 1948	[a]1963, [b]1976	631-488	631-627 - ^{137}Cs	215
299-E33-81	Nov. 1948	none	628-618	617 - 618 ^{137}Cs	< 1
299-E33-82	Nov. 1948	none	627-616	627-623 - ^{137}Cs 617-616 - ^{137}Cs	95 < 1
299-E33-15	Feb. 1953	[a]1959, [b]1976, [c]1997	628-391	409-407 - ^{137}Cs 409-391 - ^{60}Co	< 1 12
299-E33-76	Feb. 1948	[b]1976	627-489	627-621 - ^{137}Cs	4
Groundwater Wells					
299-E33-11	Jan. 1954	[a]1959, [a]1963, [a]1970	622-396	624-622 - ^{137}Cs 410-409 - ^{137}Cs 409-396 - ^{60}Co	2 < 1 8
299-E33-12	Sept. 1953	[a]1963, [a]1968, [a]1970	624-302	624-622 - ^{137}Cs 409-391 - ^{60}Co 372-302 - ^{60}Co (intermittent)	2 6 < 1

Table 4-1. Boreholes and Groundwater Monitoring Wells Logged with the SGLS and HRLS During the Investigation of the 216-B-8 Crib and Adjacent Sites

Borehole	Date Drilled	Previous Logging Review	SGLS Depth Interval Logged (Elevation, ft)	Elevation (ft) Radionuclides Detected	Maximum Concentration (pCi/g)
299-E33-13	Oct. 1953	[a]1959, [c]1992, [c]1997	629-396	628-562 - ^{137}Cs (intermittent) 427-403 - ^{137}Cs 397-396 - ^{137}Cs 531-514 - ^{60}Co (intermittent) 476-467 - ^{60}Co 413-396 - ^{60}Co	7 18 8 < 1 < 1 8
299-E33-14	Dec. 1953	[a]1959, [a]1963, [a]1970, [c]1992	622-395	412-411 - ^{137}Cs 411-395 - ^{60}Co	< 1 4
299-E33-17	Oct. 1953	[a]1959, [a]1963 [a]1968, [a]1970, [c]1997	633-392	633-632 - ^{137}Cs 416-407 - ^{137}Cs 409-392 - ^{60}Co	2 2 11
299-E33-39	Feb. 1991	[c]1997	445-396	None - well completion may preclude measurement of man-made radionuclides.	
299-E33-41	Mar. 1991	[c]1992, [c]1997	598-392	580-415 - $^{235/238}$U (intermittent)	
299-E33-44	Sept. 1998	1998 (NaI)	645-515	643-636 - ^{137}Cs borehole not logged with SGLS below 135-ft depth.	3

[a] Gross gamma or scintillation probe used prior to 1976
[b] Gross gamma system used between 1976 and 1991
[c] Radionuclide Logging System (RLS) used after 1990

5.0 Interpretation of Results

All log data collected from the boreholes and wells in the study area were assembled and correlated in an effort to identify geophysical markers, contaminated zones, and potential contaminant sources. Four cross-sections that pass through the major waste sites and connect with boreholes in the vicinity of the B, BX, and BY Tank Farms were constructed from spectral gamma logs collected within the study area and from spectral gamma logs collected in the tank farms between 1995 and 2000.

C Tech Development Corporation's Environmental Visualization System (EVS) was used to perform a geostatistical analysis of the data and to create visualizations. Visualizations generated by EVS were then selected for the report and exported to a graphics program for annotation and final presentation.

A review and comparison of historical logs shown in Table 4-1 with the current logs were conducted to identify changes over time that might affect the current interpretation.

An interpretation regarding the nature and extent of contamination for each waste site that incorporates the cross sections, visualizations, and historical data is presented. This interpretation also presents possible sources of the contamination.

5.1 Geophysical Correlation

The purpose of the geophysical correlation was to identify and correlate sedimentary features between boreholes that may influence the migration of contaminants in the vadose zone. The data acquired from 32 boreholes (Table 4-1) were interpreted and correlated with existing geophysical and stratigraphic models for the surrounding area. A simplified stratigraphic model for the B-BX-BY WMA was used as a starting point (Figure 4) to identify potential geophysical markers. The spectral gamma-ray logs for the naturally occurring isotopes (^{40}K, ^{238}U, and ^{232}Th) and total gamma logs for each borehole were compared and correlated with those from surrounding boreholes and checked for the presence of man-made radionuclides. After noting any influences of man-made radionuclides and changes in casing thickness on the spectral and total gamma logs, geophysical markers were identified.

SGLS log data from 26 of the 32 boreholes collected in the study area are shown on Cross Sections A-A' (Figure 16), B-B' (Figure 17), C-C' (Figure 18), and D-D' (Figure 19) and correlated with the existing geophysical control in the surrounding area. Figure 3 shows the locations of these cross sections. Boreholes 299-E33-79, -81, -82 in the tile field had log depths of less than 12 ft and were not included. Borehole 299-E33-74 (log depth of 143 ft) is also in the tile field and was not included because it exhibited only surface contamination and a deeper borehole was in the vicinity. Borehole 299-E33-20 was not included in a cross section because borehole 299-E33-19, 60 ft north of the borehole, provided adequate control. Borehole 299-E33-44 was not included because data acquisition was terminated at 135-ft log depth when the sonde was lost. Boreholes not logged as part of this characterization were included in cross sections to consider relationships of the waste sites to the tank farms. These boreholes were 299-E33-27 and 299-E33-45 (BX Farm), 20-00-23 (B Farm), and 299-E33-9 (BY Farm) and the logs are shown in figures 17, 18, and 19, respectively.

The cross sections serve multiple purposes. They were constructed such that 1) the nature and extent of contamination are portrayed at each major waste site, 2) relationships of contamination between sites (if any) are presented, 3) stratigraphic relationships that may affect contamination profiles can be understood, and 4) probable sources of contamination are identified.

The contaminant profile and concentration are useful as indications of the proximity of boreholes to a contaminant source. For example, ocurrences of contamination at a higher elevation suggest closer proximity to a source. Higher relative concentrations may also suggest closer proximity. By evaluating the contaminant profile in conjunction with stratigraphic correlation based on evaluation of natural gamma emitters, it may be possible to identify likely sources and probable migration pathways.

In the absence of man-made radionuclides, gamma-ray log response is generally proportional to abundance of silt and/or clay that may indicate changes in lithology. The spectral gamma-ray and total gamma-ray logs are much more useful to interpret stratigraphy than the older gross gamma-ray logs because of better sensitivity to small changes in radioactivity. The larger variations in ^{40}K content (about 5 pCi/g) appear to be correlatable between most boreholes. ^{40}K content appears to be the most reliable stratigraphic indicator.

Variations in natural radionuclides can be used to identify major changes in Hanford formation lithology. The H1 gravel facies is identified by a relatively low ^{40}K concentration of about 13 pCi/g and lower total gamma reading. The H2 sand facies is identified by a marked increase in apparent

^{40}K concentrations to about 17 pCi/g and an increase in total gamma count rate. The base of the H2 is generally defined as the point where apparent ^{40}K concentrations and total gamma count rate decrease. The H3 generally contains coarser sediment than the H2 and has gamma-ray response similar to H1; it is identified by lower total gamma count rates and ^{40}K concentrations ranging from 10 to 15 pCi/g. The H3 unit may also have occasional increases in total gamma count rate and ^{232}Th concentration. Locally correlatable layers may exist within each of these units.

5.2 Development of the Visualizations

Visualizations were prepared to illustrate the extent of contamination within the three-dimensional space that constitutes the vadose zone in the vicinity of the study area. Creating the visualizations required developing geostatistical models of the ^{137}Cs, ^{60}Co, and ^{238}U contaminant distributions. Visualizations of contamination in the vicinity of the study area include three-dimensional "sphere plots," which show contamination as detected in boreholes relative to the locations of the waste sites and the study area. Because ^{154}Eu was detected in only one borehole, it was not included in the visualizations. The contaminant models are considered empirical models because they are based on data obtained by measuring the ^{137}Cs, ^{60}Co, and ^{238}U concentrations at discrete points in the subsurface and extrapolating those values into the nearby subsurface volume. The contaminant models are not developed from assumed waste disposal and contaminant transport mechanisms, and no effort was made to calculate hypothetical distributions using contaminant transport models.

The visualizations are intended to provide the reader with an understanding of how the gamma-emitting contaminants may be distributed in the vadose zone sediments. The visualizations can also provide an assessment of the extent to which operations may have contributed to contaminant distribution and to define areas of concern for subsequent investigation.

5.2.1 Development of the Interpreted Data Set

The radionuclide concentration values derived from the SGLS and HRLS data were placed in data files that defined the position of each data point and the nuclide-specific concentration for that point. These data files were edited to create an "Interpreted Data Set" that was used to create the visualizations. The concentration data were consolidated by averaging the 0.5-ft data points over a 2.5-ft interval.

The interpreted data set reflects interpretations of the nature of the contamination based on familiarity with the distribution of contaminants gained from experience with many SGLS logs. Specific data points may be removed from the interpreted data set if they are judged to represent contamination on the outside of the casing resulting from "dragdown" during drilling, internal casing contamination from a variety of sources, or contamination that either appears to be localized to the borehole or that may be from a remote source, such as a buried pipeline. Shape factor analysis, which in certain situations can distinguish contamination in the formation from contamination that is related to the borehole casing (e.g., dragdown of contamination during drilling), was not used because the casing thicknesses were variable and not consistent with the 6-in.-diameter, 0.28-in.-thick casing for which the technique was developed (Wilson 1997). Log run overlaps are eliminated, and SGLS data are replaced with HRLS data where appropriate. The resultant concentration data are collectively referred to as the interpreted data set.

5.2.2 Three-Dimensional Visualizations

The distribution of boreholes within the study area was used to develop a three-dimensional geostatistical model. Although kriging algorithms can be used to extrapolate data, they are most effective when data points are uniformly distributed; the uncertainty increases with distance from known points. Visualizations are dependent on parameter selection as well as the subsurface data. Thus, many different visualizations are possible based on any one singular data set. The radionuclide concentration data were input to EVS subroutines that created a quadrilateral finite-element grid with kriged nodal values and output these data for viewing. The visualizations were constructed to include the highest and lowest node values in two-dimensional space. Because nodes were set up at all data sampling points, the horizontal extent of the model and the visualizations was governed by the positions of the boreholes. The model does not extrapolate beyond the extent of either the assumed range value or the kriging extent. As a result, both the model and the visualizations can only extend to the maximum depth of the boreholes and the extent of the geostatistical range.

The EVS software is an "expert" system that automatically determines parameter settings for the geostatistical model and for the kriging operation. These settings were used as a starting point for refinement of the model. Parameters were initially calculated by the software and then refined to create the most representative models for the ^{137}Cs and ^{238}U distributions.

The kriging software applied an "anisotropy ratio" that allowed the user to adjust the way values are extrapolated. The anisotropy ratio applied a bias to horizontal distances over vertical distances. The program default is 10, which means that vertical distances were multiplied by a factor of 10 before the distance between the grid point and the data point was calculated. A data point 1 ft above or below the grid point will thus appear to be 10 times farther away than a data point 1 ft away at the same level. The effect is to lessen the influence of additional data points in the same borehole. The anisotropy "forces" the kriging algorithm to give more weight to data points at the same level.

Waste sites (e.g. cribs) were visualized by creating solid rectangular three-dimensional surfaces at the locations of the crib centers. The extrapolation is not affected by the insertion of the waste sites; a borehole directly across a crib still influences the node-point concentration calculation.

5.3 Comparison to Prior Gamma Logging

A comparison of the SGLS (data acquired for this report) and RLS logs (previously acquired data) was made to determine if any significant changes in subsurface contaminant profiles have occurred. The boreholes with existing RLS logs are listed in Table 4-1, and these comparisons are detailed in the Log Data Reports included in Appendix A. Discrepancies in log depth between the SGLS and RLS measurements are typical. The cause is probably depth initialization differences between the top of casing and ground level. SGLS depth measurements are consistently referenced to the top of casing. In order to compare the measurements, the RLS data are adjusted to the more current SGLS data based on the profiles of the respective log data. RLS data are decayed to the date of the SGLS measurements where necessary to make valid comparisons.

Apparent concentrations for the man-made radionuclides show good agreement between the logging systems when the decayed concentrations are above the SGLS MDL. Other than radioactive decay, no significant changes in contaminant profile appear to have occurred in the boreholes over the time

periods between log events (3 to 10 years). Because all of these logs were collected well after discharges to the waste sites had ceased, the observed contaminant distribution appears to have been established during or shortly after the time the sites were in service and has largely stabilized over the intervening years.

Boreholes 299-E33-41 and 299-E33-18 are two exceptions. As shown in Figures 20 and 21, increases in contamination appear to have occurred in these boreholes. Log data collected in 1992 for borehole 299-E33-18 consisted of a PNNL gross gamma log that showed an interval of relatively high total counts between log depths of about 230 and 242 ft. On the basis of these data, the RLS was used to collect stationary measurements for 300 s at 236 and 252 ft. ^{60}Co was detected at both depths at less than 3 pCi/g. No $^{235/238}$U or other man-made radionuclides were reported. In 1997, the RLS was again used to log the entire borehole. ^{60}Co was detected again but $^{235/238}$U was also detected at this time. Comparison of the 1997 data with the 2001 SGLS data suggests the ^{60}Co (decayed to 2001) is stable, but the $^{235/238}$U concentrations may have increased since 1997. The entire length of borehole 299-E33-41 was logged with the RLS in 1991 and 1997. Comparison of these logs suggests a significant influx of uranium contamination between log depths of 120 and 247 ft. The SGLS log in 2002 confirms the existence of this area of contamination, and comparison with the prior logs suggests the contamination level generally has not increased since 1997. Minor increases are observed over limited depth intervals, but these may be the result of lower detection limits of the SGLS.

The gross gamma logging is the best historical record of the vadose zone contamination around the waste sites. Evaluations of previous investigators are summarized in Section 3.6. The gross gamma logging instrumentation was designed to respond in a consistent manner over the years, making it possible to compare spatial and temporal differences in relative peak count-rate spatial integrals. Unfortunately, the boreholes in the 200 Areas were not as consistently logged as in the tank farms. Once the limitations of these data are well understood, the data can be useful for assessing the general history of the vadose zone contamination. These systems were effective for high activity but were not sensitive to lower radionuclide concentrations (less than about 10 pCi/g equivalent ^{137}Cs). Data were presented as plots of the gross count rate in counts per minute (cpm) as a function of depth. Gross gamma logs were visually compared with previous data to determine, in a qualitative manner, if changes had occurred. No additional data processing or analyses were performed on these data.

When the gross gamma logs for the groundwater monitoring wells in the study area presented in Raymond and McGhan (1964), Fecht et al. (1977), and Additon et al. (1978) are interpreted based on the results of the SGLS, significant gamma-emitting contamination is observed at or below groundwater level as early as 1959. SGLS results indicate low levels of ^{60}Co, and, in some cases, ^{137}Cs just above and below the current groundwater level. In most cases, groundwater wells in the area show little or no contamination from higher in the vadose zone that appears to connect with the contamination near groundwater level. The ^{137}Cs and ^{60}Co contamination detected near groundwater level is speculated to be the result of groundwater contamination prior to 1959.

Groundwater wells 299-E33-16 and -20 near the 216-B-8 Crib and the 216-B-11A Reverse Well, respectively, also indicate the deep vadose zone ^{60}Co and ^{137}Cs contamination. Historical logs of these wells from 1959 and 1963 (Raymond and McGhan 1964) are shown in Figures 22 and 23. Both indicate probable contaminant breakthrough to the groundwater. The log comparison for borehole 299-E33-20 suggests that contamination detected throughout the borehole in 1959

consisted of gamma-emitting radionuclides that had short half lives; the 1963 profile only indicates elevated total gamma at 80 ft in depth and at the bottom of the borehole. This profile is consistent with the current SGLS log data. Data acquired from borehole 299-E33-16 showed significant contamination throughout the borehole in 1959 and 1963, although some decay had occurred. The profile is consistent with the current SGLS data, which indicates the contamination is predominantly ^{137}Cs at the present time. It should be noted that the original logs were not reviewed in this study, and the logs depicted in Raymond and McGhan (1964) are assumed as being correct representations of the logging events.

5.4 Interpretation of Contamination

As noted in Section 4.0, ^{137}Cs, ^{60}Co, and $^{235/238}$U were detected in SGLS logs in the study area. After considering the relationships between the sites using the historical log data, cross sections, and visualizations, it was determined the contamination conditions should be summarized and discussed in three areas: 1) the three major waste sites, 2) an area of $^{235/238}$ U contamination, and 3) a ^{60}Co and ^{137}Cs presence in the deep vadose zone that lies just above and within the groundwater. Visualizations of ^{137}Cs and ^{238}U are presented in Figures 24 and 25, respectively.

5.4.1 Major Waste Sites

Three major waste sites in the study area are discussed because there are sufficient numbers of boreholes associated with the sites such that an evaluation can be made. These sites include the 216-B-7A&B Cribs, the 216-B-11A&B Reverse Wells, and the 216-B-8 Crib and Tile Field.

5.4.1.1 216-B-7A&B Cribs

^{137}Cs, ^{60}Co, ^{235}U, ^{238}U, and ^{154}Eu were detected while logging in the area of the 216-B-7A&B Cribs. Figures 8, 9, and 10 are three-dimensional sphere plots that provide an enhanced perspective of the contaminant distribution of ^{137}Cs, ^{60}Co, and ^{238}U. ^{154}Eu was detected in only one borehole in the entire study area (characterization borehole C-3103); a sphere plot is not included for this radionuclide. Cross Sections B-B' and C-C' (Figures 17 and 18) pass through the vicinity of the 216-B-7A&B Cribs. Figure 3 shows the locations of the boreholes and cribs. Figure 24 provides a visualization of the ^{137}Cs contamination, the predominant contaminant detected in the vicinity of the cribs.

^{137}Cs was detected near the ground surface (elevation of about 653 ft) at each borehole in the vicinity of the cribs. The contaminated interval is at elevations ranging from 652 to 641 ft (11 ft thick) with a maximum concentration of about 10 pCi/g. The base of each crib is at an elevation of 641 ft. ^{137}Cs was measured at higher concentrations at elevations ranging between 637 and 573 ft in every borehole except 299-E33-18. The highest concentration of about 300,000 pCi/g was measured in borehole C-3103 beginning at a higher elevation (637 ft) than in the other boreholes. Data acquired from boreholes 299-E33-58 and 299-E33-60, northeast and south of borehole C-3103, respectively (Figure 3), exhibit maximum concentrations of about 4,000 pCi/g. The thickest interval (83 ft) of ^{137}Cs contamination is shown east of the cribs in borehole 299-E33-58, and the thinnest interval (29 ft) and least concentration (1,000 pCi/g) is exhibited west of the cribs in borehole 299-E33-59. Borehole 299-E33-75 indicates ^{137}Cs concentrations at about 10,000 pCi/g with the major contaminant zone beginning at a lower elevation (618 ft) in the vadose zone than boreholes in closer proximity to the cribs. The stratigraphic dip appears to be relatively flat in the west-east direction

(Cross Section B-B') and to the north (Cross Section C-C'). Boreholes 299-E33-59, -60, -58, and C-3103 appear to reflect contamination largely associated with the -7A Crib and borehole 299-E33-75 from the -7B Crib.

Borehole 299-E33-18 does not appear to exhibit contamination from the cribs, at least in the upper vadose zone, and provides an indication of the maximum areal extent of contamination to the west. Other boreholes in the area that define the maximum areal extent of contamination are 299-E33-72 (north), 299-E33-19 and 299-E33-20 (east), and 20-00-23 in the B Tank Farm (south). However, these boreholes are at relatively large distances from the cribs and thus probably overstate the actual lateral extent. Figure 24 provides a view of the ^{137}Cs contaminant distribution that indicates the contamination from the 216-B-7A and -7B Cribs probably does not extend to vicinity of the 216-B-8 Crib or the 216-B-11A&B Reverse Wells.

^{235}U and ^{238}U were detected in borehole 299-E33-59 between elevations of 612 and 600 ft. Borehole 299-E33-18, approximately 80 ft west of the cribs, exhibited $^{235/238}$U contamination between 421 and 401 ft; groundwater elevation is at 401 ft in this area. These intervals of contamination appear to be unrelated (Figures 10 and 17) and are discussed in Section 5.4.2.

^{60}Co was detected only in borehole 299-E33-18 at elevations between 422 and 410 ft, just above the groundwater, and between 403 and 394 ft partially within the groundwater. This contamination appears to be unrelated to the cribs (Figures 9 and 17).

^{154}Eu was detected only in borehole C-3103 at depths between 637 and 635 ft.

The surface contamination that lies above the base of the cribs is likely from UPR-E-121, where contaminated soil was removed and transported to the vicinity of the 216-B-7A&B Cribs and the 216-B-11A&B Reverse Wells. The contaminated soil was covered with gravel. This contamination is comprised of ^{137}Cs and is generally on the order of 10 pCi/g with a profile of 5 to 10 ft in thickness.

The area of subsurface contamination is not well defined in the area, particularly for the -7B Crib. On the basis of data acquired from borehole 299-E33-75, which is 60 ft from the -7B Crib and the stratigraphic dip (Cross Section C-C'), contamination appears to have spread laterally to the north; a slight eastward component would also be expected. Better definition of the area of contamination would require additional boreholes to be drilled northeast of the cribs approximately equidistant from the area of the 216-B-11A&B Reverse Wells and the cribs.

There is no evidence of breakthrough to the groundwater from this site, but there is only one deep borehole (C-3103) in the area. This borehole was drilled in 2001 long after deposition of contaminants between 1946 and 1967 and it did not extend to the groundwater. On the basis of comparison of historical gross gamma logs with the current SGLS data, the profile of contamination remains about the same as in 1959, indicating no significant movement.

5.4.1.2 216-B-11A&B Reverse Wells

Boreholes 299-E33-19 and -20 are located in the vicinity of the 216-B-11A&B Reverse Wells. Three-dimensional sphere plots (Figures 8, 9, and 10) include data for these boreholes. Surface ^{137}Cs contamination was measured in both boreholes at elevations ranging between 649 and 632 ft at a maximum concentration of approximately 100 pCi/g. Thin zones of contamination were detected at

elevations of 546 and 562 ft in boreholes 299-E33-19 and -20, respectively. Data acquired from borehole 299-E33-20 indicated intermittent ^{137}Cs contamination near its MDL between elevations of 564 and 448 ft with an interval between 464 and 453 ft measuring about 20 pCi/g. Both boreholes indicate ^{137}Cs contamination just above the groundwater level of 401 ft. Intervals of contamination were detected between elevations of 410 and 405 ft in borehole 299-E33-20 and between 421 and 406 ft in borehole 299-E33-19. ^{60}Co was detected at intermittent depth intervals between 536 and 520 ft in borehole 299-E33-19 and at an elevation of 429 ft in the upper vadose zone in borehole 299-E33-20. Both boreholes indicate minor amounts of ^{60}Co just above the current groundwater level.

On the basis of historical logs in borehole 299-E33-20 (Figure 23), contamination introduced to the 216-B-11A Reverse Well may have entered the groundwater prior to 1959. Current SGLS data shows ^{60}Co and ^{137}Cs were detected intermittently throughout the borehole below an elevation of 565 ft. The contamination is not as extensive in borehole 299-E33-19. Although the contamination was distributed to both reverse wells, Maxfield suggested in 1979 that the majority of contamination probably entered the 216-B-11A Reverse Well (DOE 1993a). It should be noted that some investigators have concluded that breakthrough to groundwater had occurred in the vicinity, apparently only on the basis of the connotation "Reverse Well" that is usually reserved for wells where fluid is directly injected to the groundwater. For example, one investigator stated "Reverse Wells 11A and 11B, which released fluids directly to the unconfined aquifer, …" (Wood et al. 2000), and another reported "it is safe to assume that the groundwater at this site has been contaminated with Cs-137 released from these injection wells" (Brodeur et al. 1993). The reverse wells only extend 40 ft below ground surface. The locations of the boreholes relative to the wells northwest and southeast are not well suited to intercept contamination that likely would flow to the northeast along stratigraphic dip. The 216-B-11 Reverse Wells are reported to have received about 30,000 m^3 of contaminated water (Bergeron et al. 2001), although the radionuclide inventory (Simpson et al. 2001) is low. Boreholes drilled northeast of the reverse wells would be useful to better determine the nature and extent of the contamination.

As shown in Figures 24 and 25, the visualizations of contaminant distribution suggest that contamination from the 216-B-7A&B Cribs did not migrate to the vicinity of the reverse wells.

5.4.1.3 216-B-8 Crib and Tile Field

Sphere plots for the 216-B-8 Crib and Tile Field are shown in Figures 11 through 13. ^{137}Cs was the predominant contaminant detected in this area. Contamination is detected near the ground surface between 642- and 629-ft elevation with a maximum concentration of about 300 pCi/g. A second interval of higher concentration ^{137}Cs contamination was detected at elevations between 622 and 495 ft. The maximum concentration measured was about 150,000 pCi/g in borehole 299-E33-67, which is in closest proximity to the 216-B-8 Crib. Borehole 299-E33-89 exhibits the beginning of a major interval of contamination at 621 ft in elevation; the bottom of the crib is at 625 ft. The thickest interval of contamination measured near the crib is also in this borehole. Borehole 299-E33-16 is the deepest borehole in the vicinity of the crib and exhibits almost continuous contamination throughout the borehole. Boreholes northeast of the crib in the tile field exhibit only near-surface contamination.

Portions of Cross Sections A-A' and C-C' (Figures 16 and 18) pass through the area of the crib and tile field. The H1/H2 interface is at about 613 ft in elevation in the area and generally appears flat in

the vicinity of the crib and tile field. The surface cannot be determined in most boreholes because the KUT is not measured in the high gamma flux zones. The ^{137}Cs contamination appears to begin at the H1/H2 interface.

^{60}Co was detected only in the deep boreholes (i.e., 299-E33-11, -15, and -16 in Cross Section C-C') at elevations between 409 and 391 ft.

Historical logs (Raymond and McGhan 1964) of borehole 299-E33-16 (Figure 22) show contamination probably entered groundwater sometime prior to 1959.

5.4.2 U-235/U-238 Contamination

Two boreholes (299-E33-18 and -41) in the study area exhibit $^{235/238}U$ contamination. Uranium was detected in only one other borehole (299-E33-59), which is in the vicinity of the 216-B-7A&B Cribs. Cross Section B-B' (Figure 17) shows the profiles of the uranium in these boreholes. The cross section originates from borehole 299-E33-27, which is near tank BX-102 in the BX Tank Farm. Tank BX-102 is reported to have lost about 91,600 gallons of metal waste, including about 22.5 tons of uranium, through a faulty spare inlet port (Wood et al. 2000). Although borehole 299-E33-27 only exhibits ^{137}Cs contamination, the cross section shows the magnitude and depth of contamination. Because of the very high gamma flux caused by the ^{137}Cs, the SGLS cannot measure the uranium isotopes. Because ^{137}Cs tends to adsorb to the sediments near the source, the more mobile uranium can be detected a short distance away in the absence of the ^{137}Cs. SGLS logging conducted by MACTEC-ERS (DOE 2000b) identified uranium contamination east-northeast of tank BX-102 in 1997 in numerous boreholes that had been drilled in 1971 (Womack and Larkin 1971). In addition, MACTEC-ERS determined from a limited repeat logging program conducted in 1999 that uranium appeared to be moving through the vadose zone in the area to the east of the BX Tank Farm (DOE 2000b). Because the boreholes in the area were not advanced below 150 ft in depth, the true vertical extent of contamination is unknown. Borehole 299-E33-45 was drilled to groundwater in January 2001 in the center of known contamination. The SGLS measured uranium contamination to a log depth of 198 ft (elevation of 462 ft). Borehole 299-E33-41 was drilled between January and April 1991. As discussed in Section 5.3, comparisons of log data have been made from this borehole that indicated an influx of $^{235/238}U$ into the area of the borehole between 1991 and 1997. Perched water was encountered in this borehole when it was drilled at a depth of 224 ft from the ground surface (elevation of 431 ft). Sediments were described as moist to wet for the rest of the section (Narbutovskih 1998). An elevated water table was also observed that drained rapidly by about 6.6 ft during a single month. In the months prior to drilling the well, several flooding events occurred just south of this well's location at 244-BX-DCRT. The migration through the vadose zone of water from these flooding events would explain the perched water, unusually moist soils reported during drilling, and the temporary elevated water table (Narbutovskih 1998). This source of moisture would also provide a driving mechanism for uranium migration through the vadose zone.

As discussed in Section 5.3, borehole 299-E33-18 also showed an influx of uranium contamination between 1992 and 1997 and contaminant concentrations appear to continue to be increasing in 2002. This borehole is located 240 ft east-northeast of borehole 299-E33-41 and appears to be situated down stratigraphic dip. Cross Section B-B' suggests the uranium contamination is migrating laterally and downward through the vadose zone. Borehole C-3103 was drilled in 2001 for the purpose of characterizing the 216-B-7A&B Cribs and is located about 80 ft from borehole 299-E33-18. High moisture content was encountered in a silt lens at an elevation of about 434 ft and

drilling was terminated. This high moisture content is about 3 ft higher in elevation than that encountered in borehole 299-E33-41 in 1991 but it is at the same elevation where contamination increases were indicated when comparing the 1991 and 1997 log data. This high moisture content in 299-E33-41 may be related to the possible flooding events from the 244-BX-DCRT (Narbutovskih 1998). It is possible the uranium contamination has migrated past the location of borehole C-3103. Figure 25 is a visualization of the area of uranium contamination. This visualization suggests that contamination from the overflow event at tank BX-102 probably reached groundwater between boreholes 299-E33-41 and -18. The interpreted data set generated from the BX Tank Farm geophysical log data reported in DOE (2000b) are combined with the uranium data collected for this characterization. The data set is limited by the lack of deep wells in the vicinity of tank BX-102 (maximum log depth of 150 ft) and a lack of control north of the area of contamination. Logging was not completed with the SGLS in borehole 299-E33-44 because the sonde was lost (it has since been recovered). This borehole is located 330 ft north of borehole 299-E33-41. A sodium-iodide (NaI) system was used to log this borehole in 1998. No contamination was detected in the borehole at that time, although the relatively short counting time of 30 s and the relatively poor resolution typical of NaI systems may not have been sufficient to detect low levels of uranium contamination. The location of borehole 299-E33-44 is key to understanding the northward extent of the uranium contamination. This borehole should be logged as soon as possible, after the cause of the sonde loss has been determined and measures have been implemented to prevent another hang-up inside the casing.

5.4.3 Co-60 and Cs-137 Contamination near Groundwater Level

Thirteen deep boreholes/groundwater wells were logged in the study area (Table 5-1). Ten of these wells are referred to as non-compliant RCRA groundwater wells that were drilled in the 1950s. Three wells are RCRA-compliant drilled in the 1990s. Table 5-1 indicates the dates drilled, type of well, intervals of contamination that lie within the H3 stratigraphic unit that are just above or within the groundwater, the maximum concentration measured, and comments where appropriate. Table 4-1, Section 4, includes further information for these wells and other boreholes in the study area.

Table 5-1. Groundwater Monitoring Wells Logged with the SGLS

Borehole/ Groundwater Well No.	Date Drilled	Type	Interval of Deep Contamination Below the H2/H3 Interface	Maximum Concentration (pCi/g)	Comment
299-E33-11	Jan. 1954	Non-compliant	410-409 - ^{137}Cs 409-396 - ^{60}Co	< 1 8	
299-E33-12	Sept. 1953	Non-compliant	409-391 - ^{60}Co 372-302 - ^{60}Co (intermittent)	6 < 1	Contamination extends into the basalt
299-E33-13	Oct. 1953	Non-compliant	427-403 - ^{137}Cs 397-396 - ^{137}Cs 413-396 - ^{60}Co	18 8 8	^{60}Co detected in the upper vadose zone
299-E33-14	Dec. 1953	Non-compliant	412-411 - ^{137}Cs 411-395 - ^{60}Co	< 1 4	
299-E33-15	Feb. 1953	Non-compliant	409-407 - ^{137}Cs 409-391 - ^{60}Co	< 1 12	
299-E33-16	Jan. 1953	Non-compliant	425-419 - ^{60}Co 404-389 - ^{60}Co	< 1 6	
299-E33-17	Oct. 1953	Non-compliant	416-407 - ^{137}Cs 409-392 - ^{60}Co	2 11	
299-E33-18	Feb. 1950	Non-compliant	421-401 - $^{235/238}$U 422-410 - ^{60}Co 403-394 - ^{60}Co	50/600 2 < 1	
299-E33-19	June 1956	Non-compliant	421-406 - ^{137}Cs 424-420 - ^{60}Co 408-405 - ^{60}Co	3 < 1 < 1	Well no longer intercepts groundwater
299-E33-20	July 1956	Non-compliant	410-407 - ^{137}Cs 405-402 - ^{60}Co	2 < 1	
299-E33-39	Feb. 1991	Compliant	None	None - well completion may preclude measurement of man-made radionuclides	
299-E33-41	Mar. 1991	Compliant	580-415 - $^{235/238}$U (intermittent)	40/1,000	No ^{137}Cs or ^{60}Co
299-E33-44	Sept. 1998	Compliant	None	Logged in 1998 with (NaI) system borehole not logged below 135-ft log depth with SGLS	

Spectral gamma logging of the 10 non-compliant wells indicates minor amounts of ^{60}Co (less than 10 pCi/g) in each well and minor amounts of ^{137}Cs in seven wells (less than 20 pCi/g) just above and within the current groundwater level. The contamination is generally sporadic or non-existent in the upper vadose zone except in boreholes that are located within a contaminated waste site (Figures13 through 15). All of these boreholes were drilled in the 1950s. Boreholes drilled more recently such as 299-E33-41, -39, and -44 do not exhibit any ^{137}Cs or ^{60}Co contamination in depth intervals near the groundwater; -44 was logged to groundwater with a NaI detection system. Uranium contamination was detected in 299-E33-18 and -41 just above the groundwater but it is not believed to be associated with the ^{137}Cs or ^{60}Co contamination.

The groundwater is postulated to have been significantly contaminated in the 1950s, perhaps from the BY Cribs north of the BY Tank Farm, some of the waste sites in the area, and/or from tank wastes. The ^{137}Cs and ^{60}Co contamination may have had been adsorbed to rust inside the steel pipe. As the groundwater receded over the years a "bathtub ring" was formed on the inside of the casing,

which resulted in apparent contamination above the current groundwater. Therefore, the apparent contamination may be an artifact of an historical groundwater plume and not representative of contamination distributed in the formation. The lack of contamination in the three recently drilled RCRA-compliant wells would support this hypothesis. However, these three RCRA wells have a large annular space filled with material such as bentonite and sand that is not conducive to logging and may impede measurement of gamma rays from the formation by the SGLS. Furthermore, ^{60}Co has been detected near its quantitation limit in groundwater samples from boreholes 299-E33-13 and -16.

5.5 Potential Uncertainties and Inaccuracies

The interpretations discussed above are subject to a relatively high degree of uncertainty because of the number and distribution of boreholes with respect to the waste sites; consequently, the horizontal and vertical extents of the vadose zone contamination are poorly controlled.

The construction of most boreholes is documented in the form of drilling logs. Most of the drilling logs provide varying degrees of detail regarding the drilling operations, geologic descriptions of sediments penetrated by the drilling, radioactivity encountered during drilling, and a description of the construction configurations of the "as-built" boreholes. Geologic descriptions are subjective and the depth control can vary by as much as 5 ft. The drilling logs provide information regarding when and how the boreholes were drilled and document the occurrences of radiological contamination that were encountered during drilling.

6.0 Conclusions

Thirty-two boreholes were logged with the SGLS in the area of surrounding waste sites northeast of the B-BX-BY Waste Management Area. Gamma-emitting radionuclide concentration data were generated for naturally occurring and man-made radionuclides at 0.5-ft intervals; several deep boreholes were logged at 1-ft intervals. Logging results were used to create a baseline data set for this collection of waste sites. Log Data Reports and log plots were prepared and published separately for each individual borehole. The Log Data Reports provide a history of boreholes and place the SGLS log data into an appropriate format to be used for waste site remediation and monitoring.

Empirical ^{137}Cs and $^{235/238}$U contamination distribution models were created. These cross sections and models were used to create visualizations of the contamination distribution that were discussed in this report. Data collected between 1995 and 1999 for the tank farms baseline characterization were incorporated with the current characterization data to evaluate the relationships of contamination and stratigraphy. A review of historical information was conducted to integrate with current information when interpreting the data. The information relating to the contamination distribution beneath the study area can be used to locate additional characterization boreholes, implement a monitoring program, to provide input for risk assessment calculations, and for planning site environmental activities.

^{137}Cs, ^{60}Co, ^{235}U, ^{238}U, and ^{154}Eu were detected while logging in this study area. Three major waste sites (216-B-7A&B Cribs, 216-B-8 Crib and Tile Field, and the 216-B-11A&B Reverse Wells) in the study area contained sufficient boreholes such that an evaluation could be made. In general, each site exhibited ^{137}Cs contamination as the predominant contaminant, with the highest concentration measuring 300,000 pCi/g in the vicinity of the 216B-7A&B Cribs. Historical log information collected after 1959 suggested the possibility of contaminant breakthrough to the groundwater in the vicinity of the 216-B-8 Crib and Tile Field and the 216-B-11A&B Reverse Wells. Because the area of the 216-B-7A&B Cribs did not have a deep borehole in the immediate vicinity in the late 1950s, the possibility of an historical breakthrough of contamination to groundwater could not be evaluated for that site. With the exception of borehole 299-E33-16 in the 216-B-8 Crib area and borehole 299-E33-20 in the vicinity of the 216-B-11A Reverse Well, the contamination profiles for each waste site show that significant site-related contamination is generally not detected below a log depth of 150 ft. ^{137}Cs and ^{60}Co that are detected near the groundwater/vadose zone interface are probably largely the result of contamination from a distant source such as the BY Cribs that may have contaminated the groundwater prior to 1959. There generally is not a continuous record of contamination from the high concentration zones above 150-ft log depth to the deep vadose zone. Waste from individual sites may have entered the groundwater at some time; however, the relative contributions cannot be determined. The contamination in boreholes in the three waste sites does not appear to correlate and it is unlikely the wastes have commingled, at least in the upper vadose zone. A comparison of the profiles of historical gross gamma logs and current SGLS logs as well as a more direct comparison of more recent RLS spectral logs with the SGLS suggest contamination profiles and concentrations at the waste sites are relatively stable over time.

Other sites in the area that contained waste such as the 216-B-51 French Drain, 244-BX-DCRT, 241-B-252 Diversion Box, and the 241-B-301 Catch Tank do not have boreholes in close proximity and thus the presence or absence of contamination in the immediate vicinity cannot be evaluated.

An area of uranium contamination originating from the BX Tank Farm was identified just above groundwater in borehole 299-E33-18 at a lateral distance of 400 ft from its presumed source at tank BX-102. This contamination apparently was mobilized by an external water line leak that created a high moisture zone at about 5 ft above the normal water table in the area northeast of the BX Tank Farm. This contamination apparently reached boreholes 299-E33-41 and -18 between 1991 and 1997. SGLS logging suggests the area of uranium contamination is relatively stable in borehole 299-E33-41 but may have increased in borehole 299-E33-18 since 1997. The high moisture identified at the bottom of borehole C-3103 may be related to the deep moisture zone identified in borehole 299-E33-41 and may contain uranium contamination. Uranium migration may be following the northeast stratigraphic dip in this area.

^{137}Cs and ^{60}Co contamination were detected in all deep boreholes drilled in the 1950s at a depth consistent with historical and current water levels. Boreholes drilled to the groundwater in the area since the 1990s did not exhibit any contamination. Although this may be related to differences in well construction, the contamination is postulated to be derived from groundwater contamination present in the 1950s. The contamination observed by the SGLS may have been adsorbed by rust and scale inside the casing and does not represent formation contamination. Further investigation of this possibility is needed. The source of the historical $^{60}Co/^{137}Cs$ contamination could be the BY Cribs. Data visualizations suggest that the BY Tank Farm may also be a potential source of the contamination.

Geophysical interpretations also include a limited evaluation of the stratigraphic relationships between boreholes. Increases in the ^{40}K concentration define the contact between the Hanford H1 and H2 units that may represent a potential spreading surface for contaminants. The H1/H2 surface was correlated to predict the direction of lateral migration in the vadose zone. The elevation is estimated at about 630 ft in the southwest to about 605 ft in the northeast. The contact between the Hanford H2 and H3 ranges in elevation from 440 ft in the southwest to 430 ft in the northeast. The base of the H2 is defined when apparent ^{40}K concentrations decrease and total gamma increases. The H3 is identified by lower readings on the total gamma logs and readings ranging from 10 to 15 pCi/g on the ^{40}K logs with occasional increases in total gamma and ^{232}Th. Changes in the ^{40}K content appear to have a greater influence on the total gamma-ray logs than the other naturally occurring radionuclides.

Although questions remain about the true nature and extent of the ^{137}Cs, ^{60}Co, and uranium contamination, a baseline has been established for the study area. Future monitoring can be conducted to determine if the contamination is moving, where the contamination is going, and if additional sources are present.

7.0 Recommendations

The vadose zone characterization of the study area was conducted to establish a baseline value for gamma radionuclide activities in vadose zone sediments surrounding the waste sites. This baseline can be used to compare with future monitoring data to determine if changes have occurred and to assess the rate and potential causes of the changes. The data from this characterization project can also be correlated and compared with information other than concentration data, such as moisture data.

Historical logging performed in this area is poorly documented. Additional work is recommended to collect, catalog, digitize, assess, and analyze historical gross gamma logging results for this area. Some work on collecting historical logs has been performed and presented in various publications that present only a fraction of the logs and are usually little more than a collection of logs with limited analysis results. This work is recommended to be continued and expanded to include all available logging results.

Initial characterization within the study area has identified several areas where future characterization efforts should be conducted. The 216-B-7A&B and the 216-B-8 Crib and Tile Field are reasonably well characterized, although the lateral extent of contamination is poorly defined. An additional borehole is recommended to the northeast of each of the -7A and -7B Cribs. These boreholes should extend to groundwater to assure the uranium contamination from the BX Tank Farm is detected, if present. Moisture measurements should be made to detect any variations in moisture content and to locate zones of high moisture content that appear to transport uranium contamination. Soil samples should be obtained from the vadose zone/groundwater interface to provide confirmation as to whether the occurrences of ^{137}Cs and ^{60}Co in older groundwater wells is distributed in the formation or is adsorbed to the inside of the casings. A borehole should be drilled east of borehole 299-E33-16 to define the lateral extent of ^{137}Cs contamination in the 216-B-8 Crib and tile area.

The boreholes used to monitor the 216-B-11A and -11B Reverse Wells are 299-E33-20 and -19, respectively. The locations of the boreholes relative to the reverse wells are southwest and northwest and are not ideal to intercept possible contamination that likely would flow to the northeast along stratigraphic dip. It is recommended a borehole be drilled northeast of the 216-B-11A Reverse Well to groundwater to detect any contamination originating from the reverse wells and to further define the extent of the uranium contamination.

The area of ^{238}U contamination should be further defined and monitored. In addition to determining its extent in the east-northeast direction past the 216-B-7A&B Cribs, the area northeast of the BX Tank Farm (perhaps about 150 ft northeast of borehole 299-E33-41) should be investigated. Borehole 299-E33-44 should be relogged with a sonde that can enter the 4-in. borehole. This borehole is key to understanding the contamination profile because of its proximity to the BY Farm and its location midway between boreholes 299-E33-41 and -13, which in addition to 299-E33-44 both exhibit uranium contamination in the groundwater. Any new boreholes and existing boreholes that are related to the area of contamination should be placed in a monitoring program to measure contaminant movement. Selected boreholes in the BX Tank Farm are currently being monitored with the Radionuclide Assessment System. This system is less complicated than the SGLS and provides data suitable for monitoring purposes, and it should be used in selected boreholes to track migration of the uranium contamination.

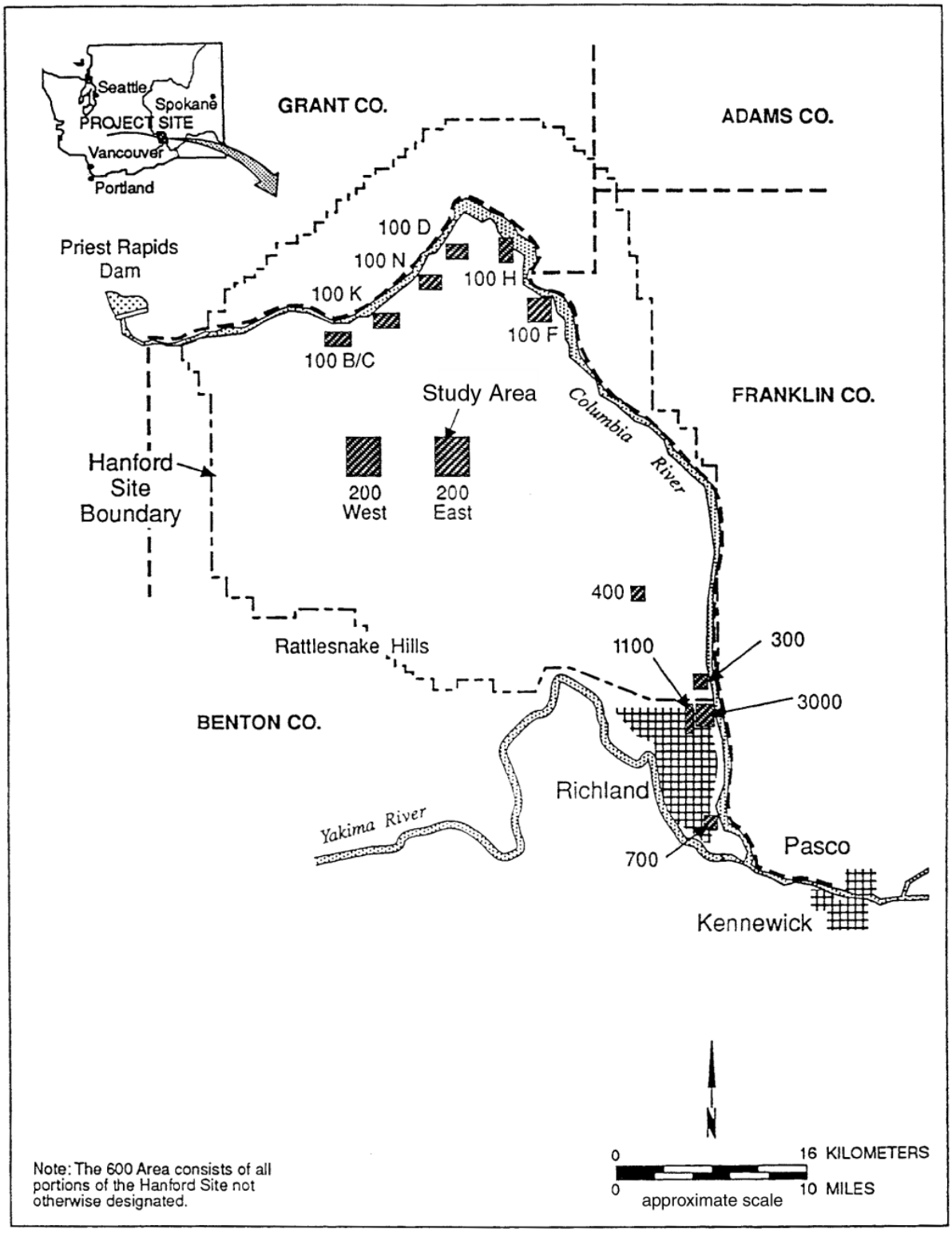
Other waste disposal sites in the study area such as the 216-B-51 French Drain, 244-BX-DCRT, 241-B-252 Diversion Box, and the 241-B-301 Catch Tank do not have any boreholes in close proximity and thus the nature and extent of any subsurface contamination cannot be evaluated. Boreholes should be drilled at these sites to determine if contamination is present. Moisture measurements should also be collected in existing and future boreholes throughout the study area because water is apparently the primary driving force for uranium migration.

Any additional vadose zone characterization boreholes should include sampling and laboratory analysis for radionuclides and chemical contaminants that do not emit gamma radiation (e.g., ^{90}Sr and ^{99}Tc).

Although borehole geophysical methods do not provide a comprehensive characterization dataset, the methods are useful because they are cost effective and safe and because numerous existing boreholes allow access to the subsurface. Other borehole geophysical methods, such as neutron moisture, neutron capture, passive neutron and gamma-density logging, are recommended for development and implementation at the Hanford Site to provide better characterization data. These techniques should become part of an overall vadose zone characterization.

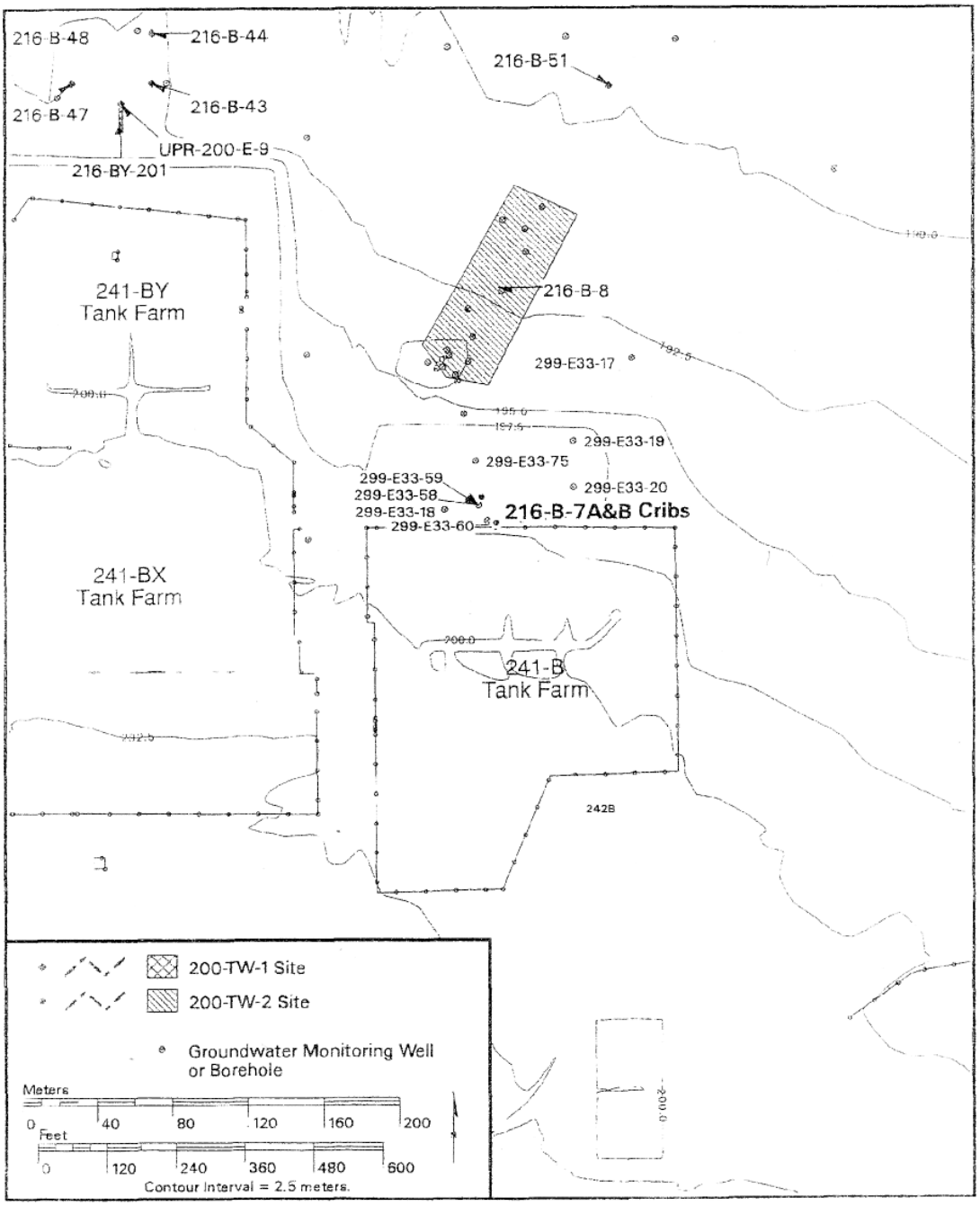
Figures

The following section presents the figures cited in this report in the order in which they were presented.



modified from DOE (1993b)

Figure 1. Hanford Site and Area Designations



from DOE (2000d)

Figure 2. Map of the B-BX-BY Waste Management Area Showing the Locations of the 216-B-8 Crib and Adjacent Waste Sites

216-B-8 Crib and Adjacent Sites

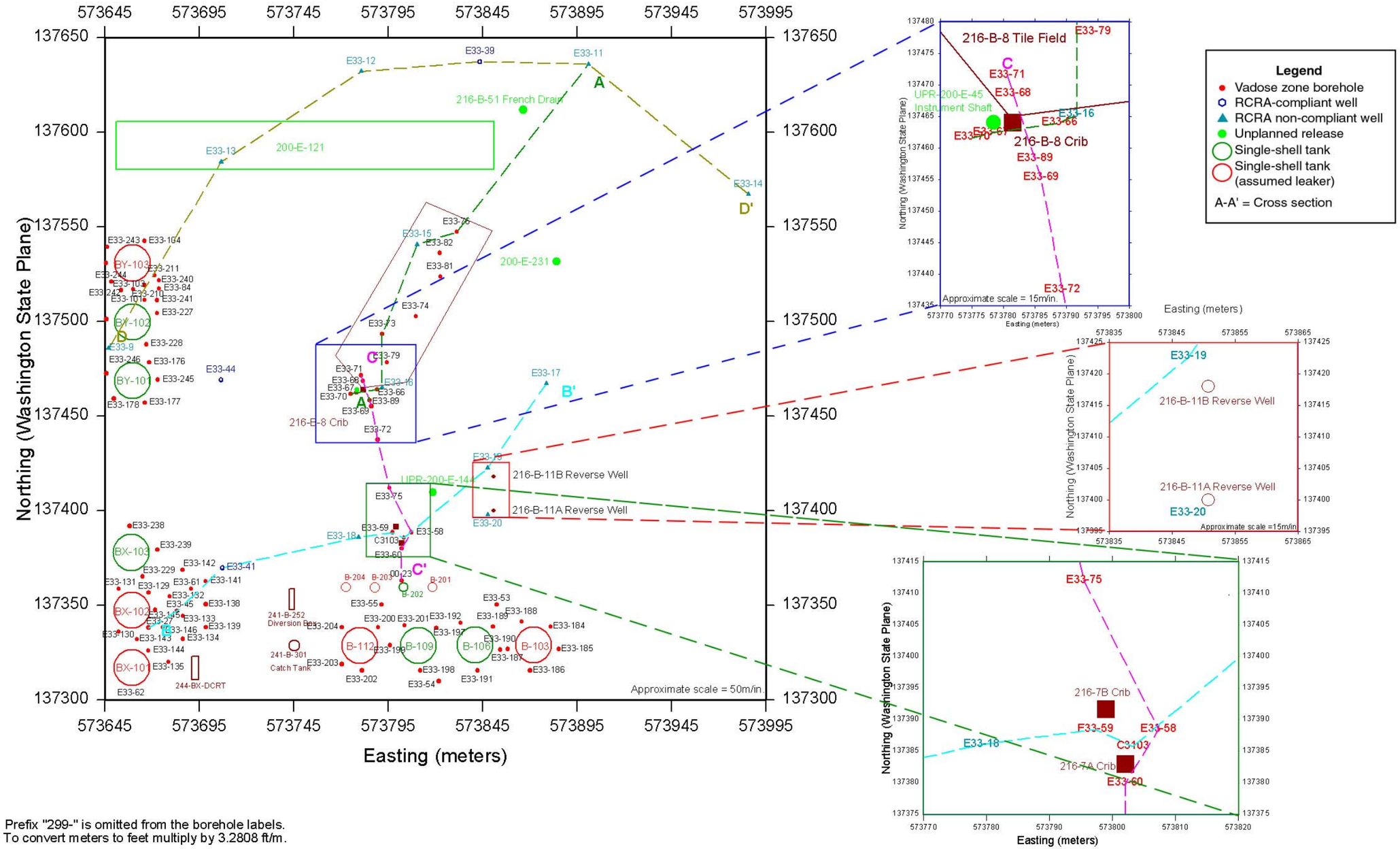
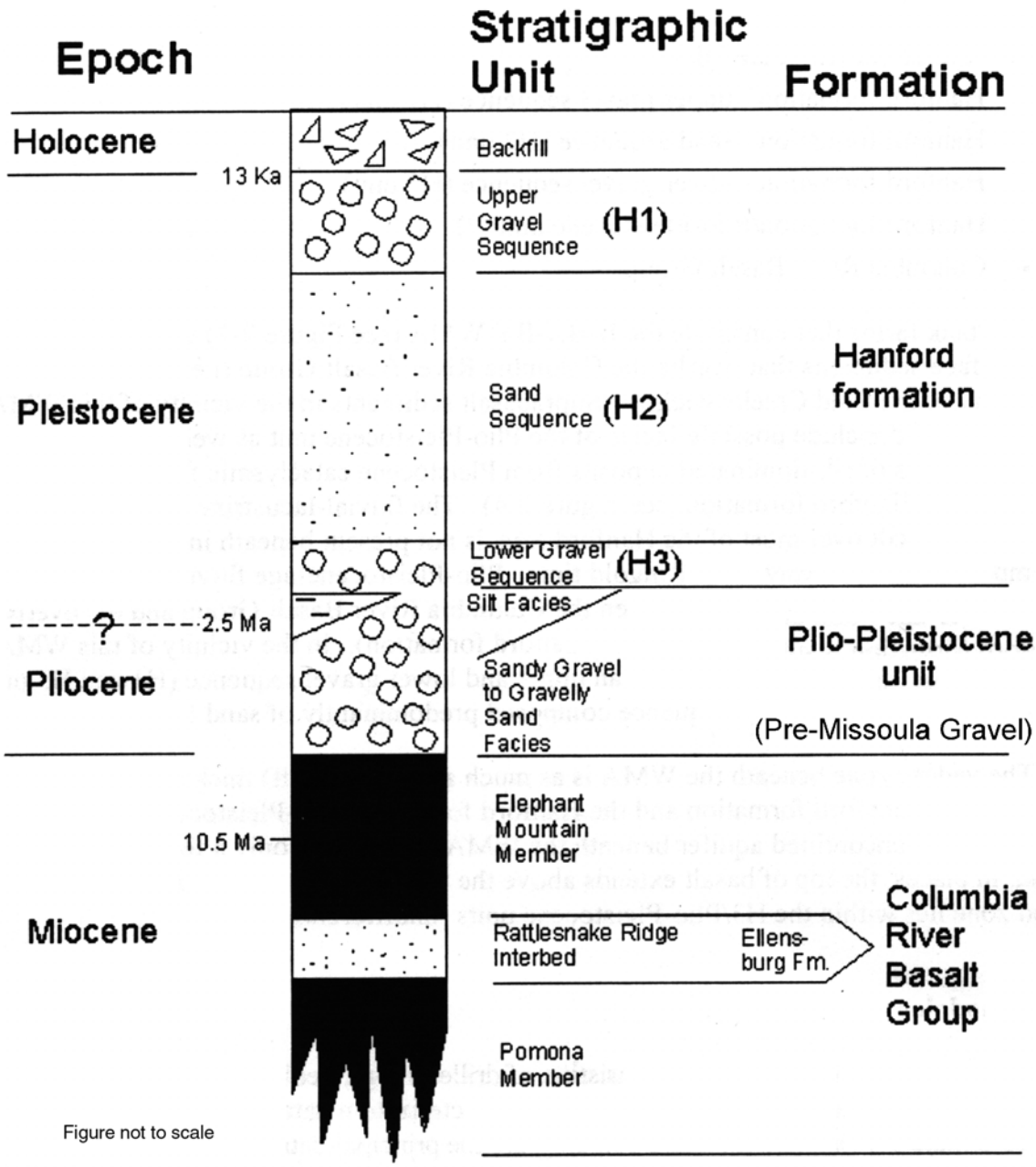


Figure 3. Map of the 216-B-8 Crib and Adjacent Waste Sites, Boreholes, and Cross Sections



Modified from Wood et al. (2001)

Figure 4. General Stratigraphy of the B-BX-BY Waste Management Area

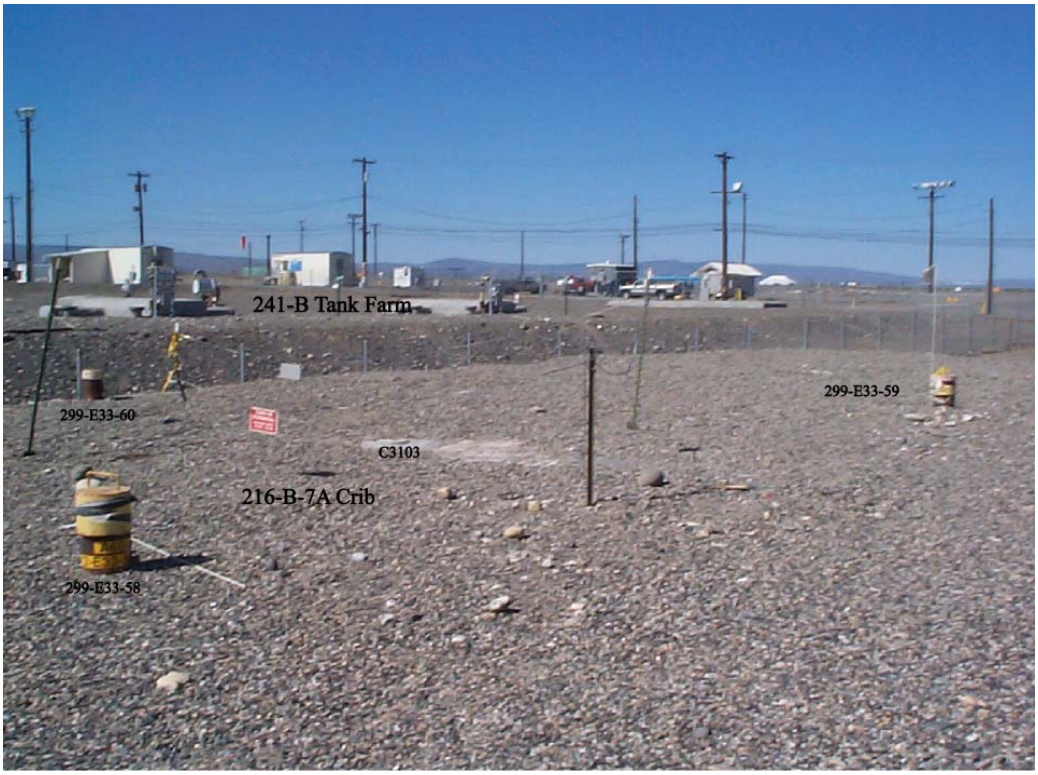


Figure 5a. View of the 216-B-7A Crib from the Northeast

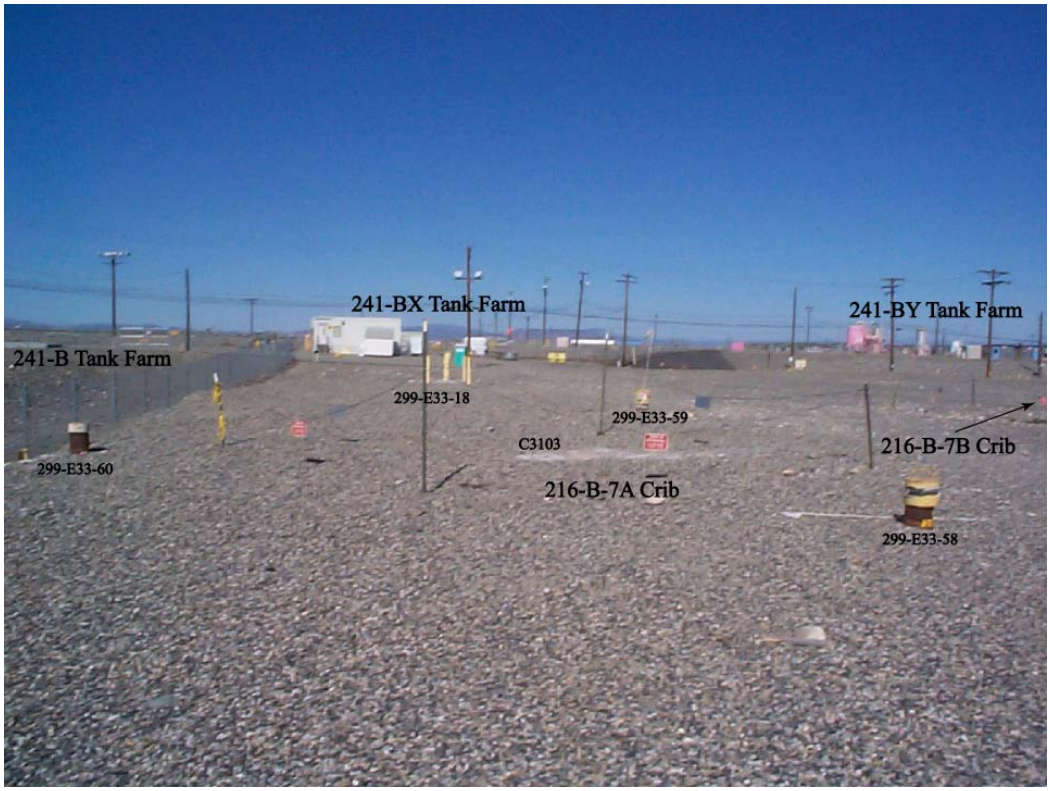


Figure 5b. View of the 216-B-7A&7B Cribs from the East

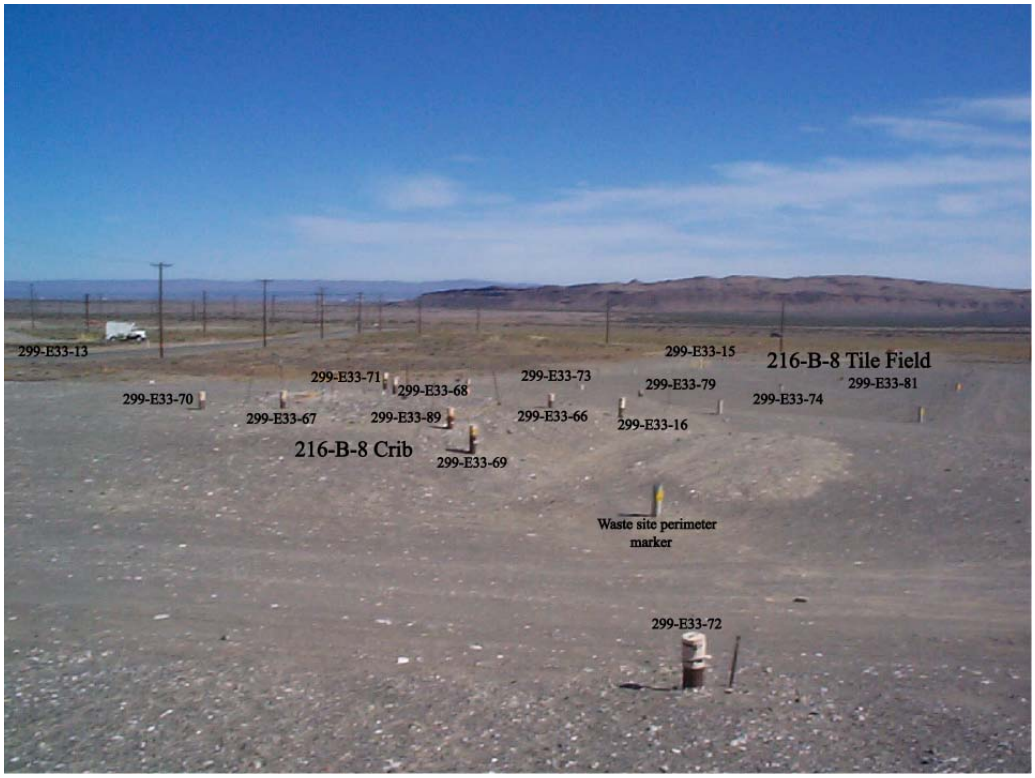


Figure 6a. View of the 216-B-8 Crib and Tile Field from the South

Figure 6b. View of the 216-B-8 Crib from the Northeast

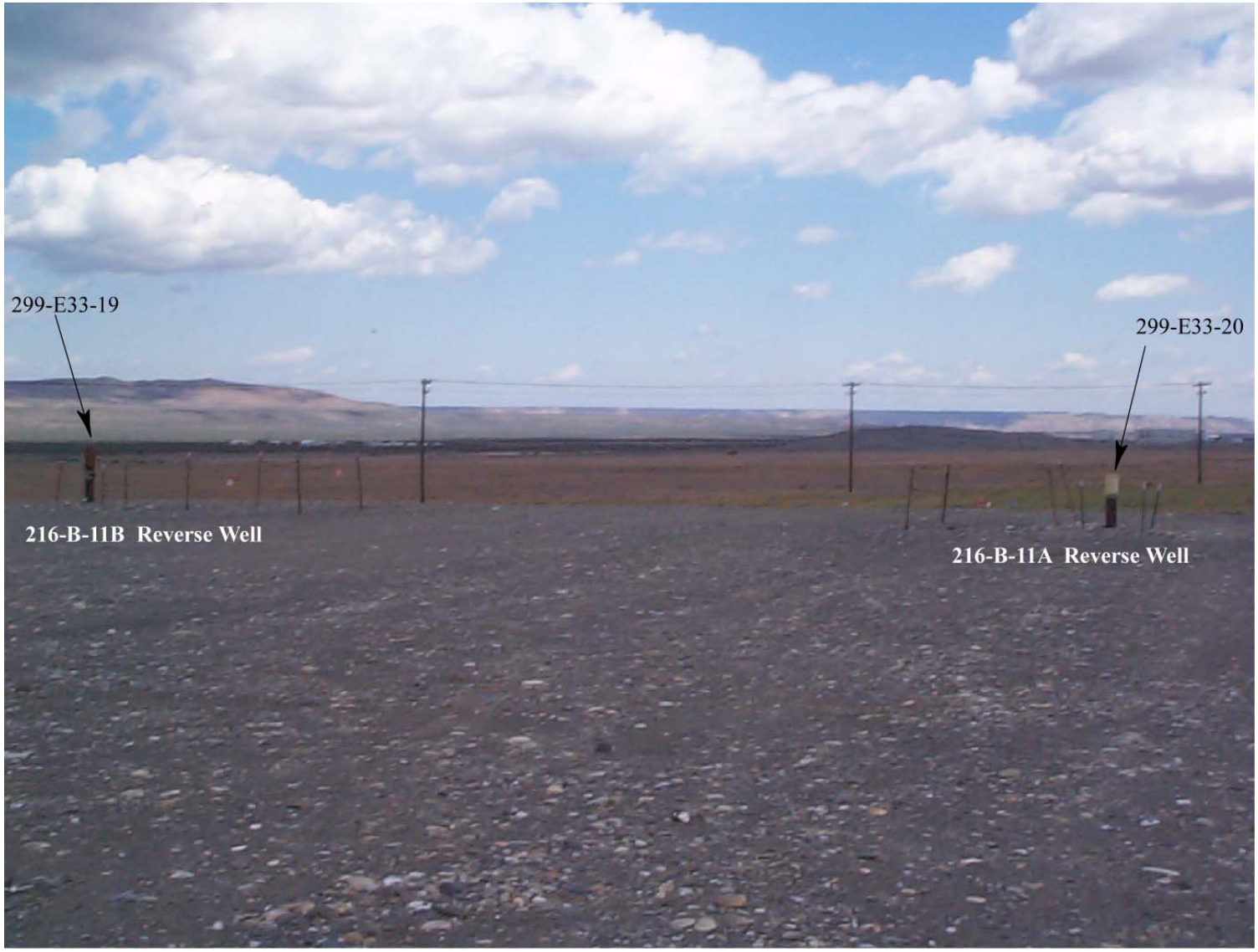


Figure 7. View of the Area Surrounding the 216-B-11A and -11B Reverse Wells from the Southwest

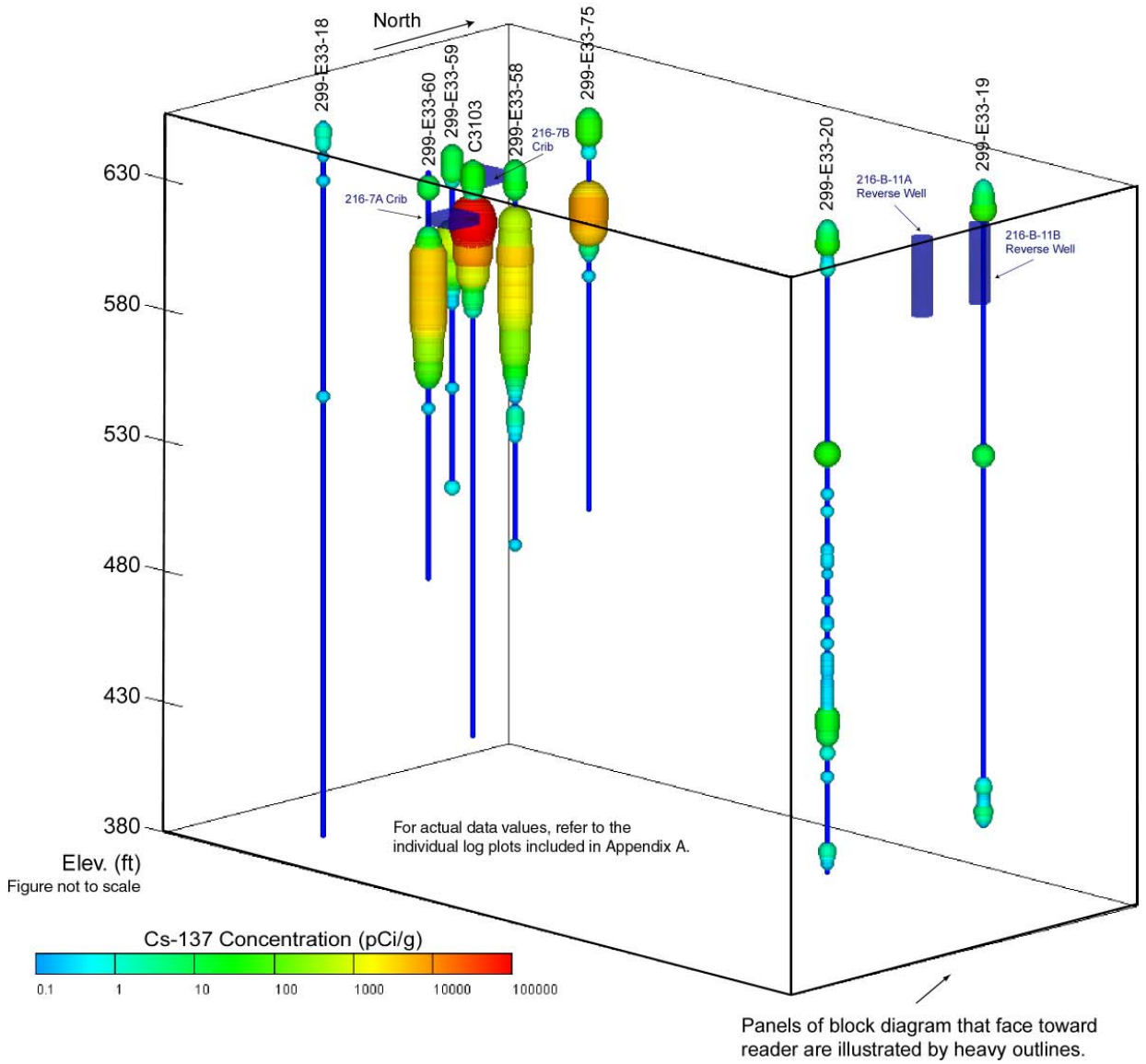


Figure 8. Visualization of the Cs-137 Data Acquired at the 216-B-7A and -7B Cribs and the 216-B-11A and -11B Reverse Wells

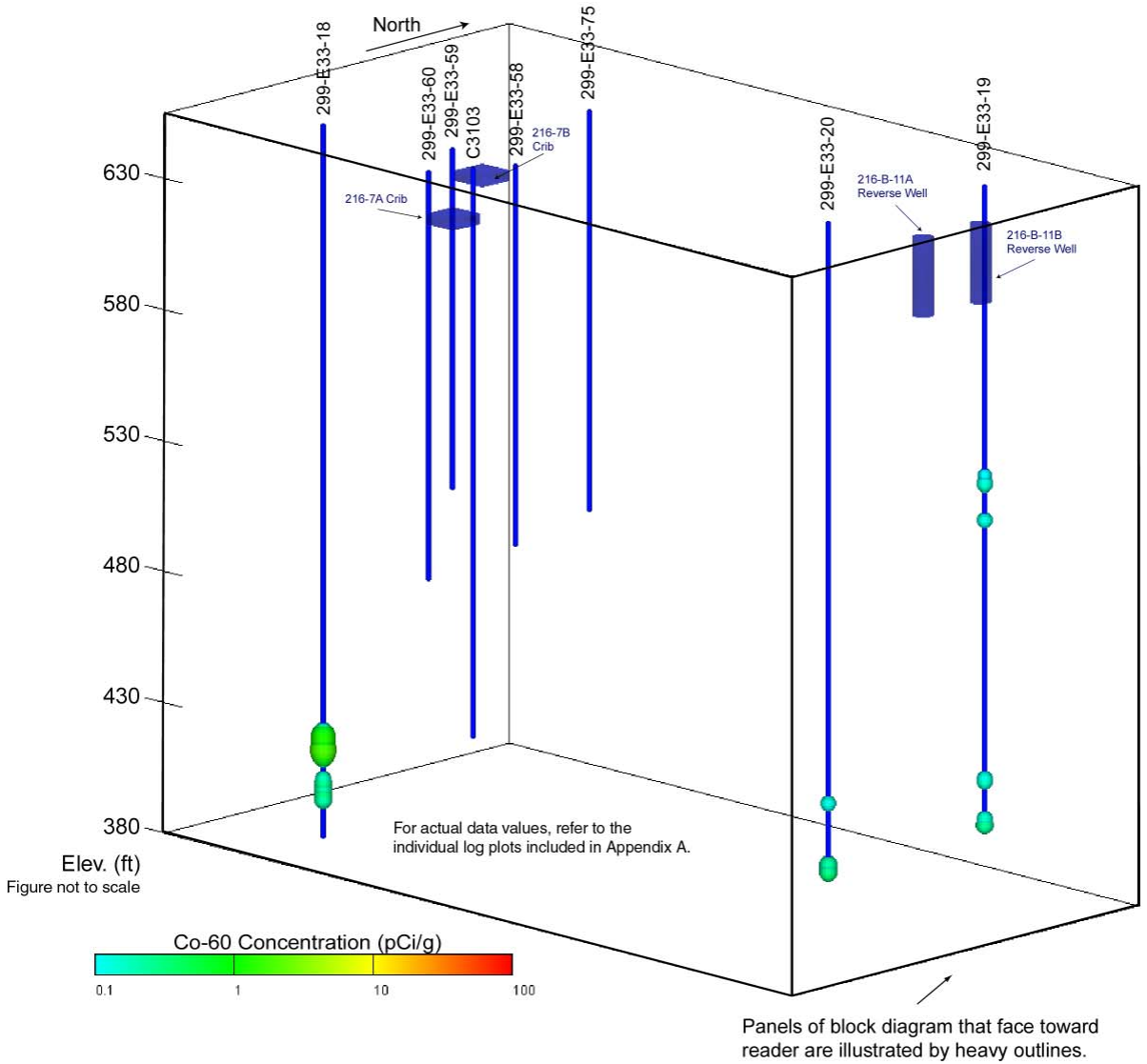


Figure 9. Visualization of the Co-60 Data Acquired at the 216-B-7A and -7B Cribs and the 216-B-11A and -11B Reverse Wells

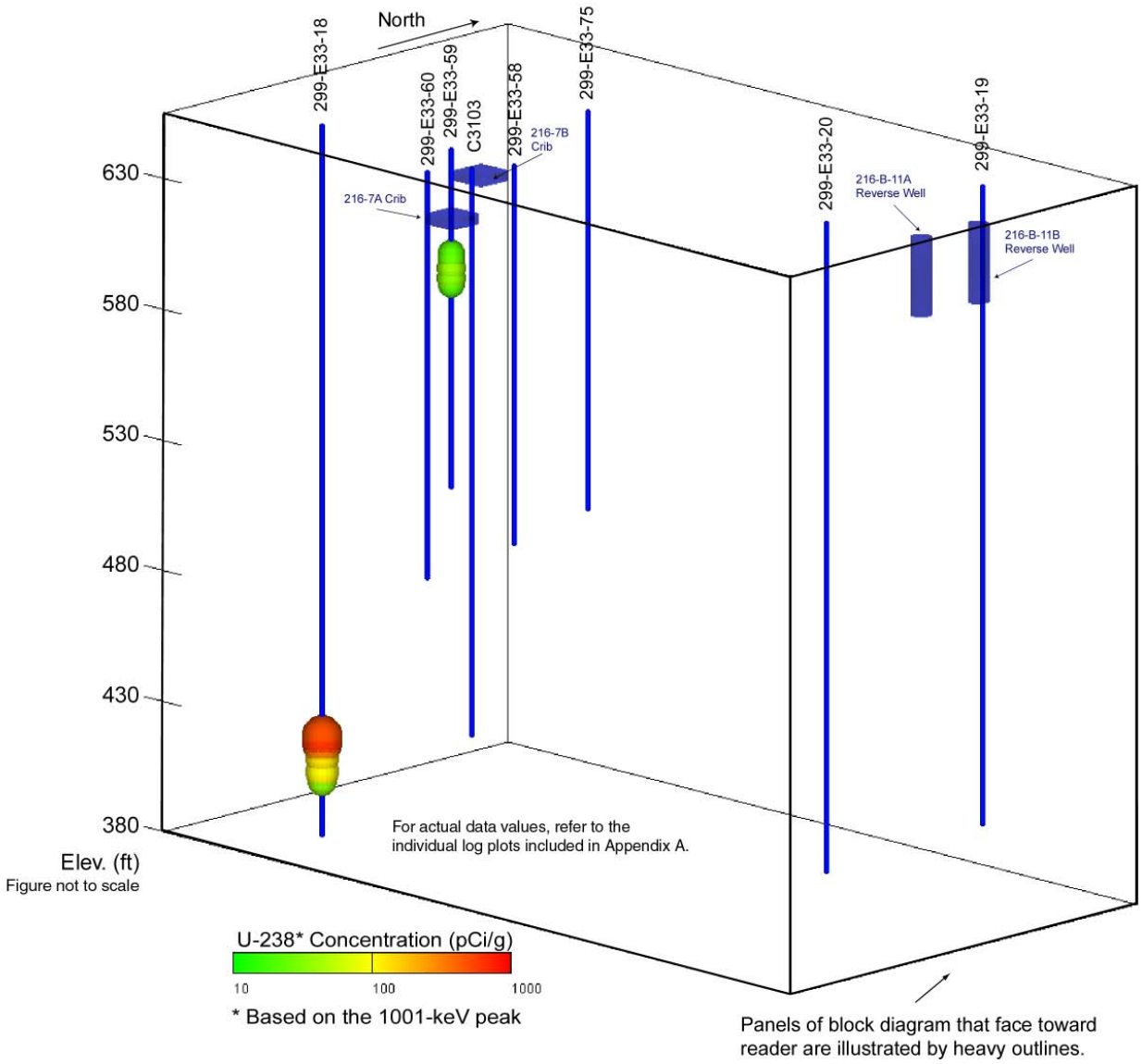


Figure 10. Visualization of the U-238 Data Acquired at the 216-B-7A and -7B Cribs and the 216-B-11A and -11B Reverse Wells

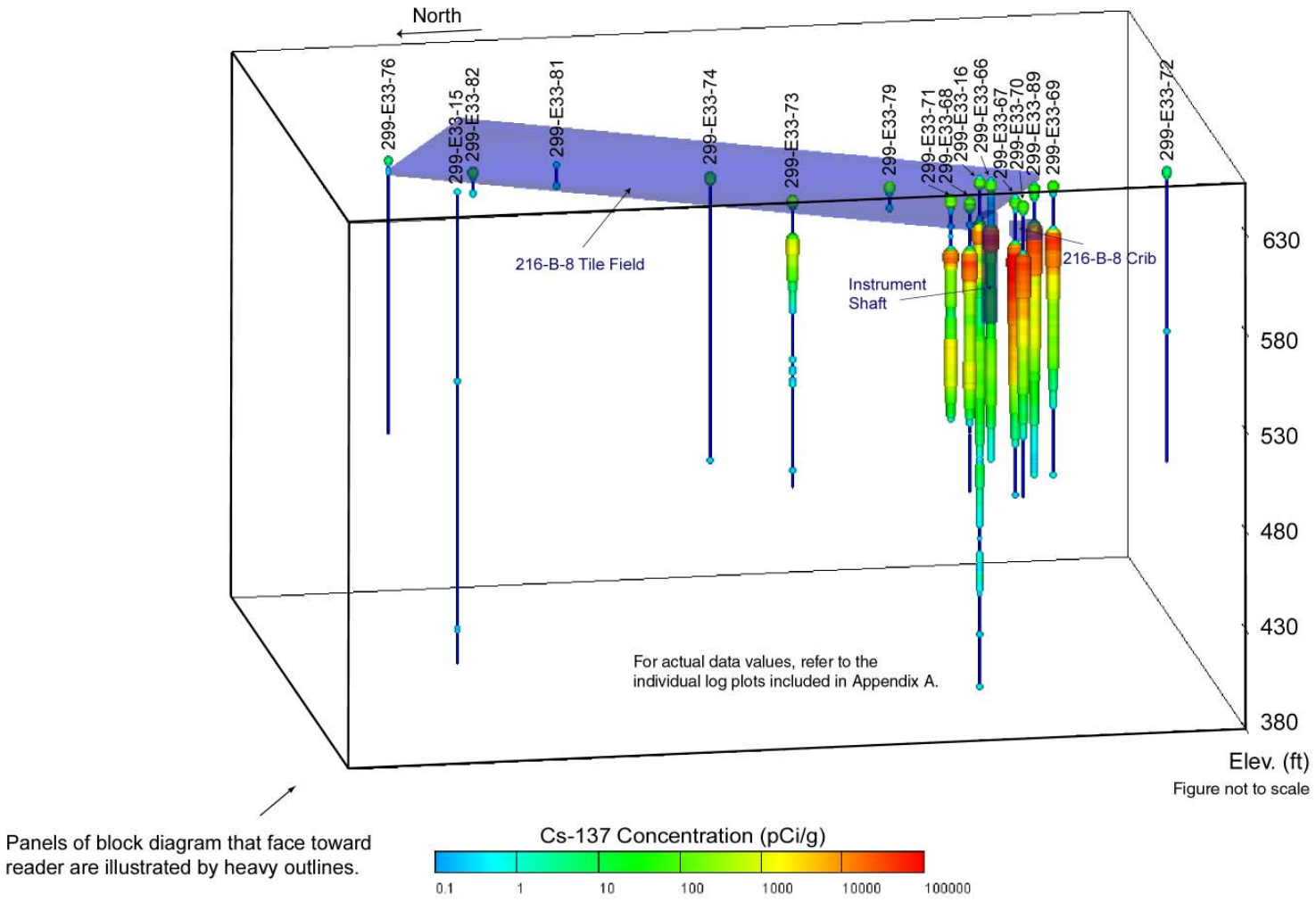


Figure 11. Visualization of the Cs-137 Data Acquired at the 216-B-8 Crib and Tile Field

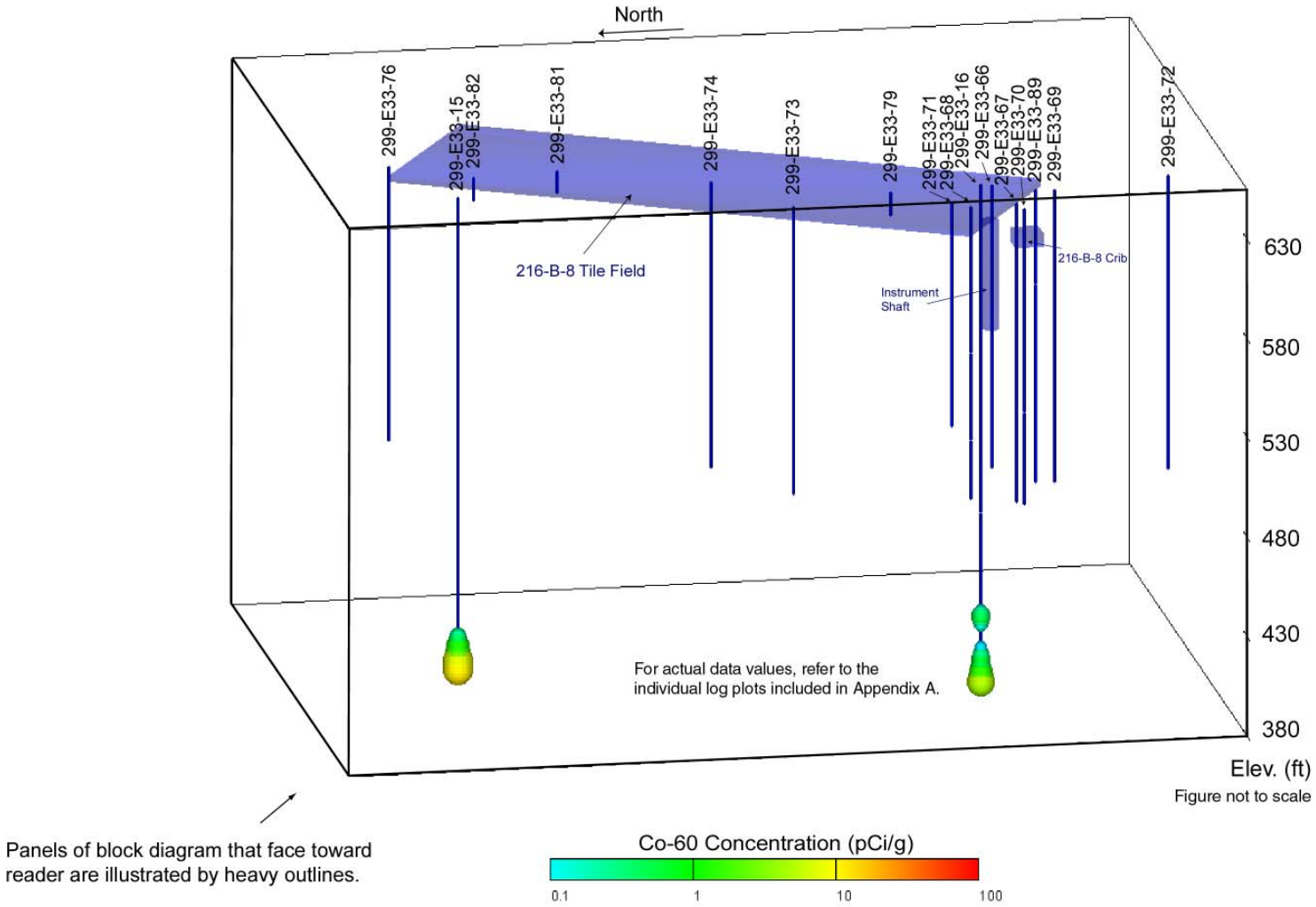


Figure 12. Visualization of the Co-60 Data Acquired at the 216-B-8 Crib and Tile Field

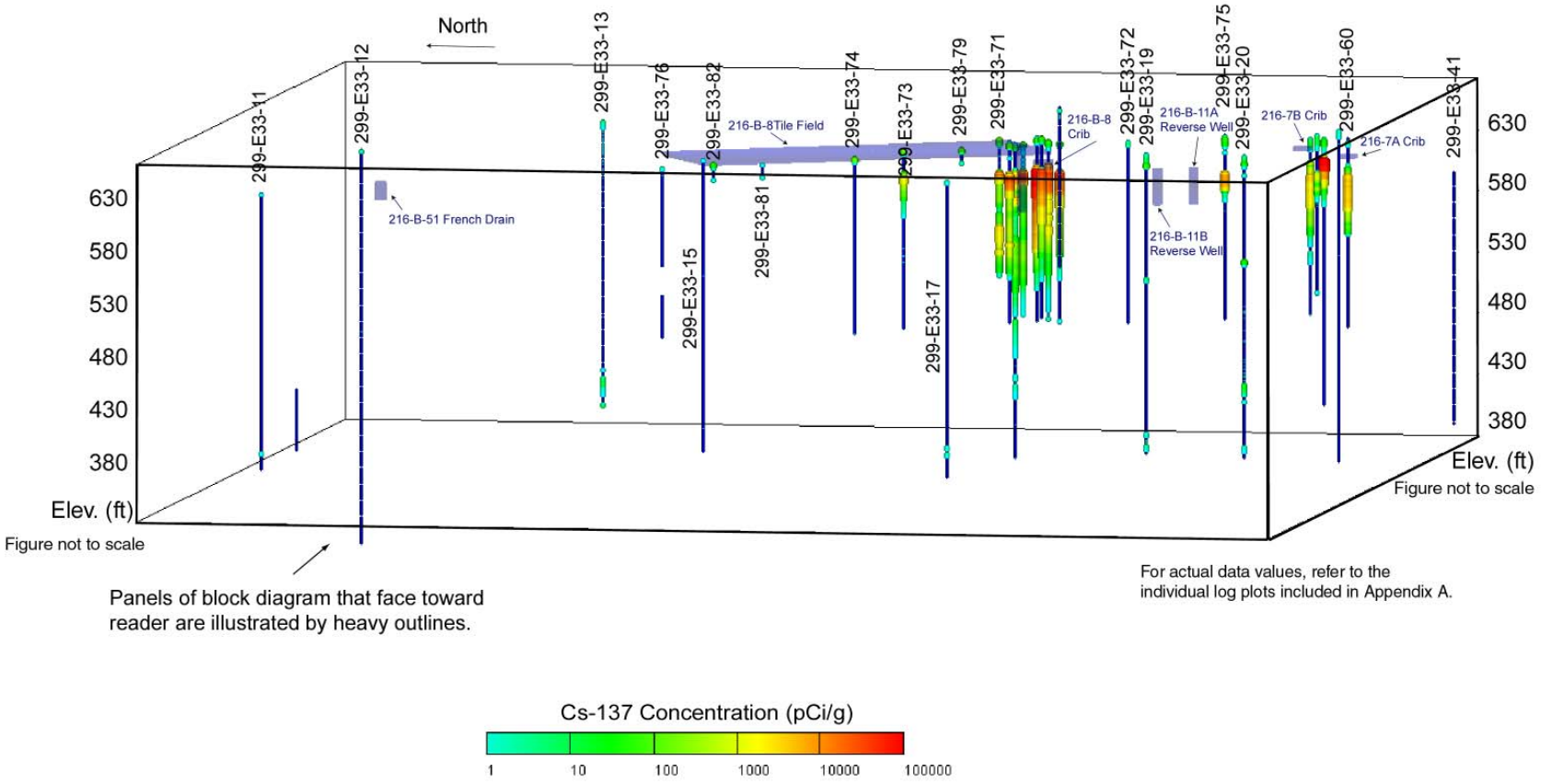


Figure 13. Visualization of the Cs-137 Data for the 216-B-8 Crib and Adjacent Sites

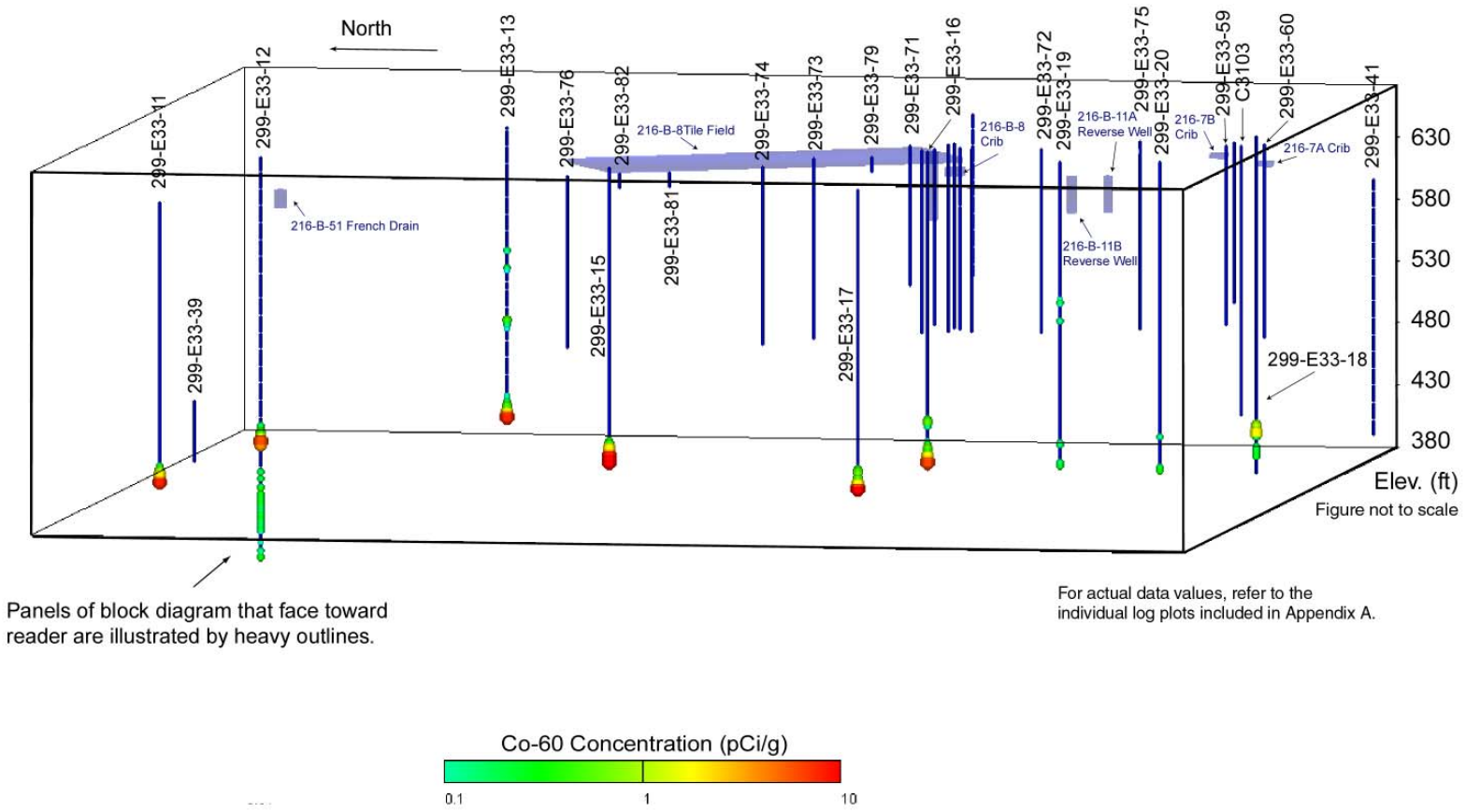


Figure 14. Visualization of the Co-60 Data for the 216-B-8 Crib and Adjacent Sites

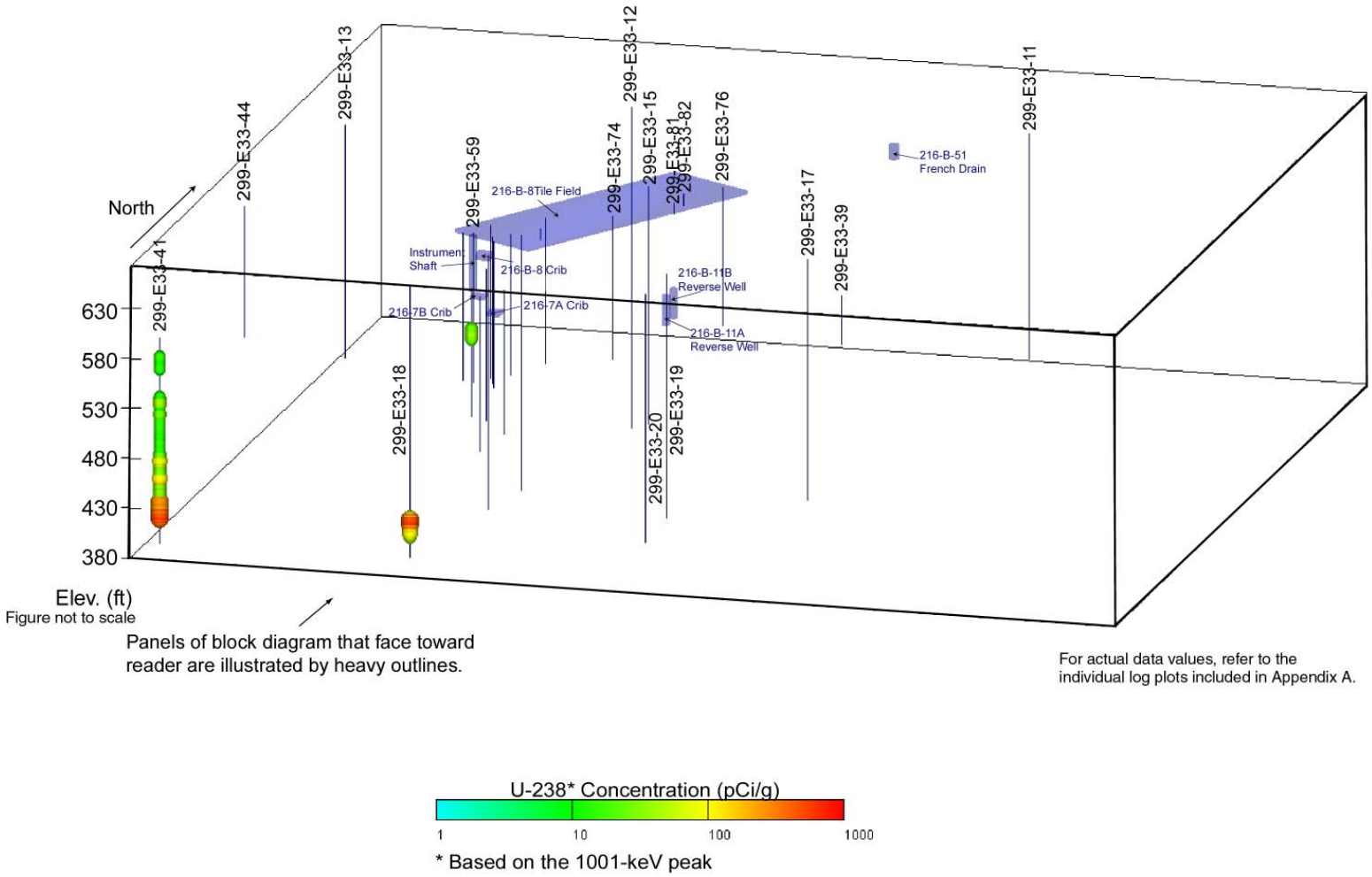


Figure 15. Visualization of the U-238 Data for the 216-B-8 Crib and Adjacent Sites

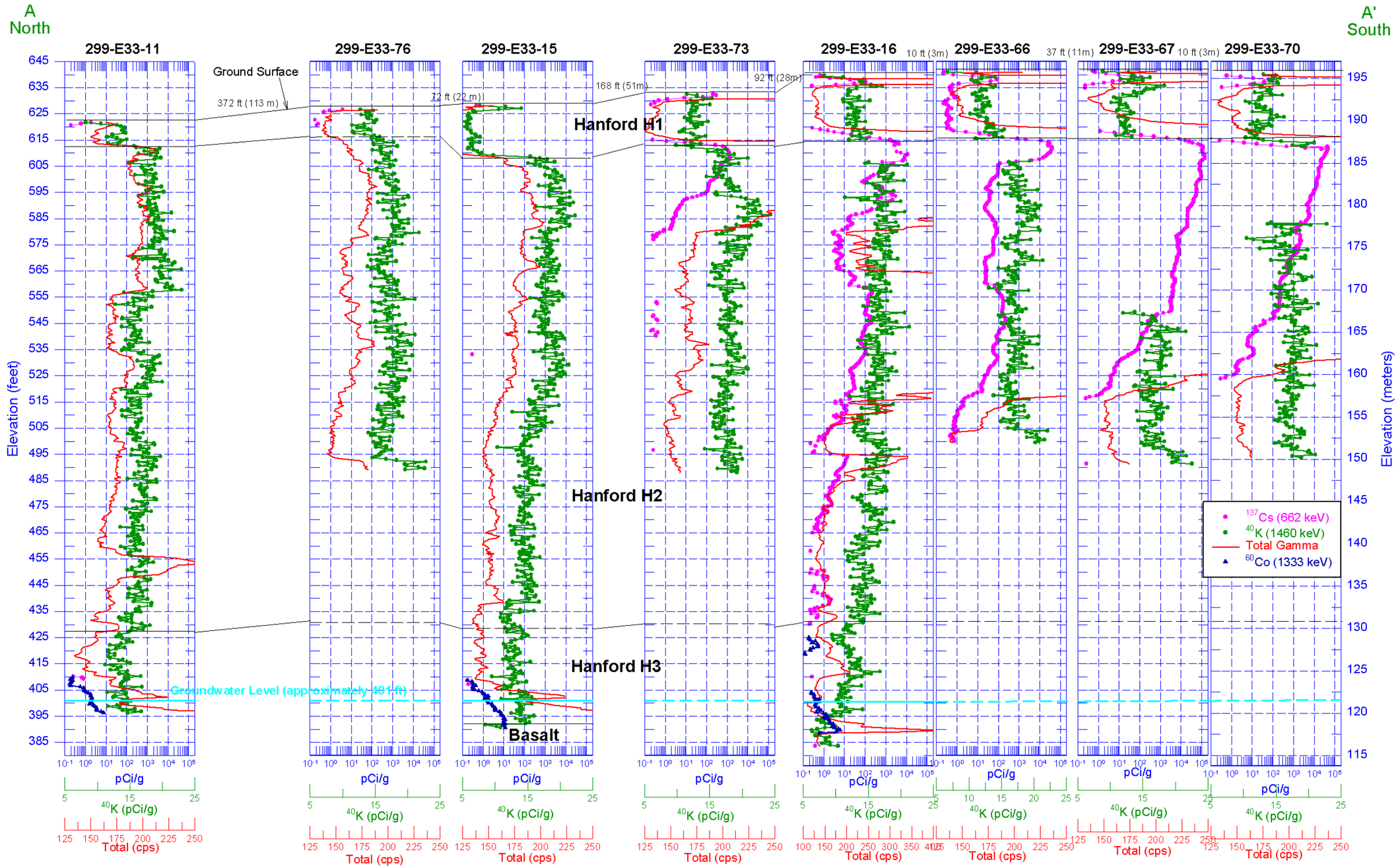


Figure 16. Cross Section A-A' Showing Contamination and Interpreted Stratigraphy Along the 216-B-8 Crib and Tile Field

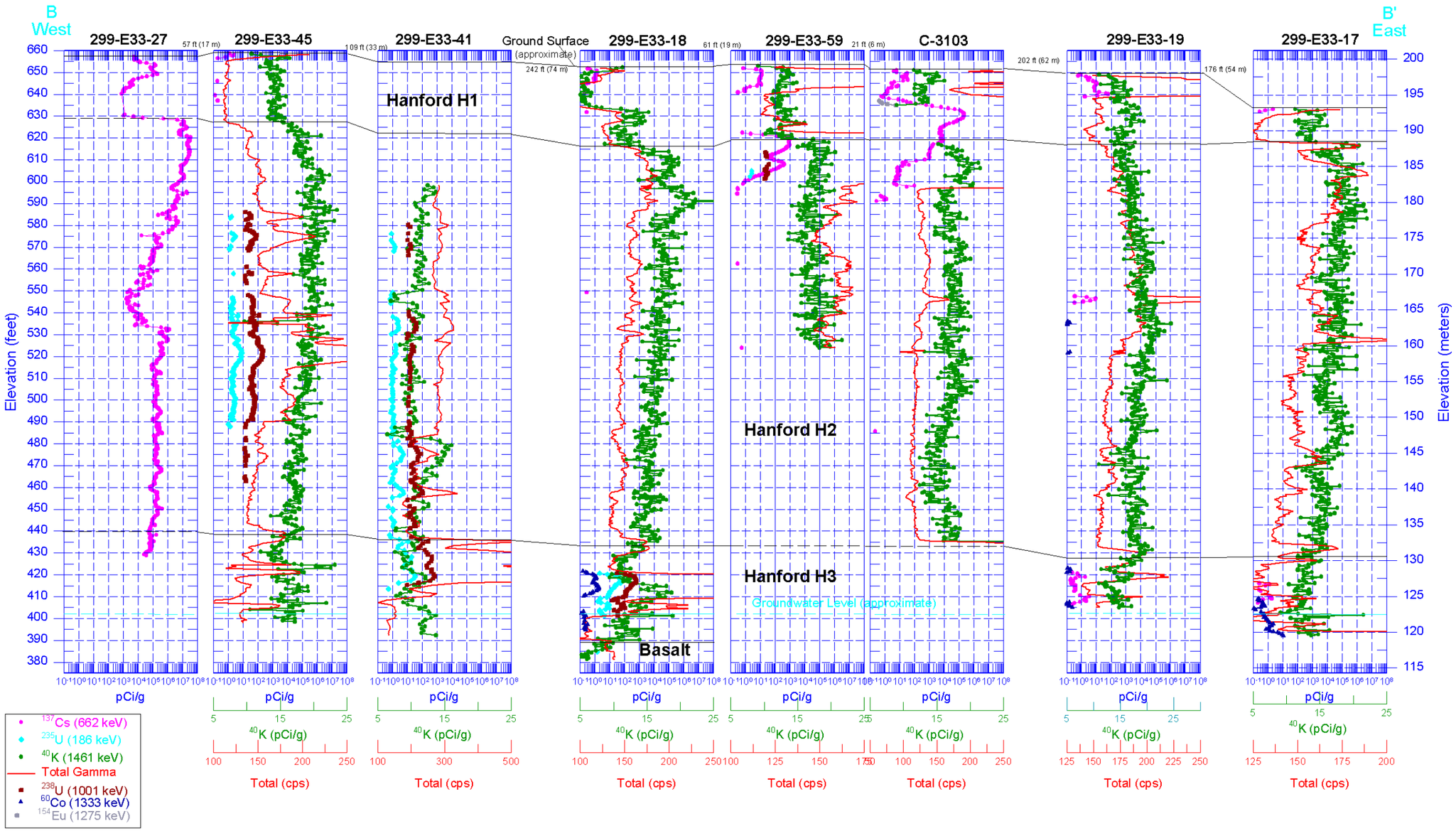


Figure 17. Cross Section B-B' Showing Contamination and Interpreted Stratigraphy Along the 216-B-7A and -7B Cribs and the 216-B-11A and -11B Reverse Wells

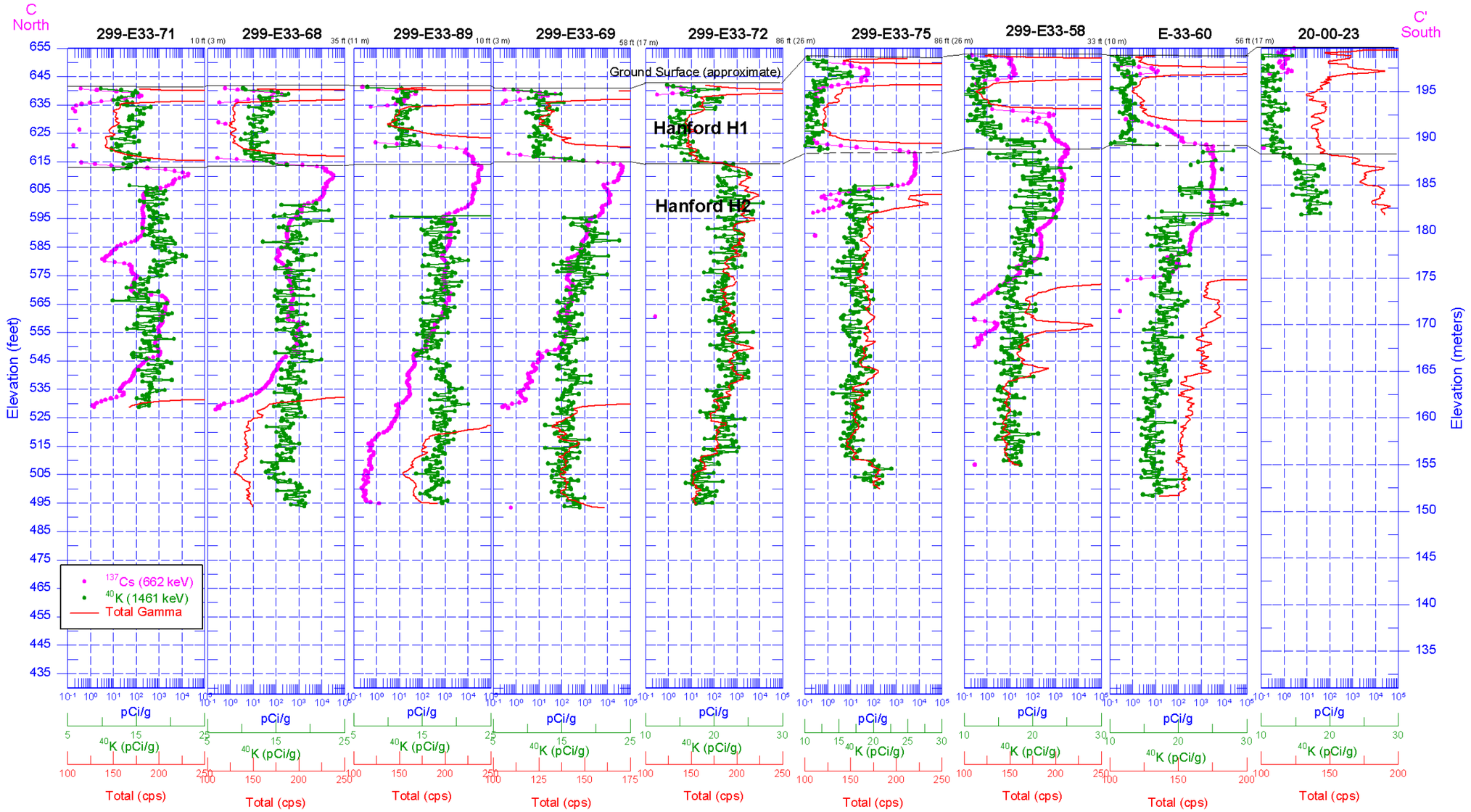


Figure 18. Cross Section C-C' Showing Contamination and Interpreted Stratigraphy Along the 216-B-8 Crib and the 216-B-7A and -7B Cribs

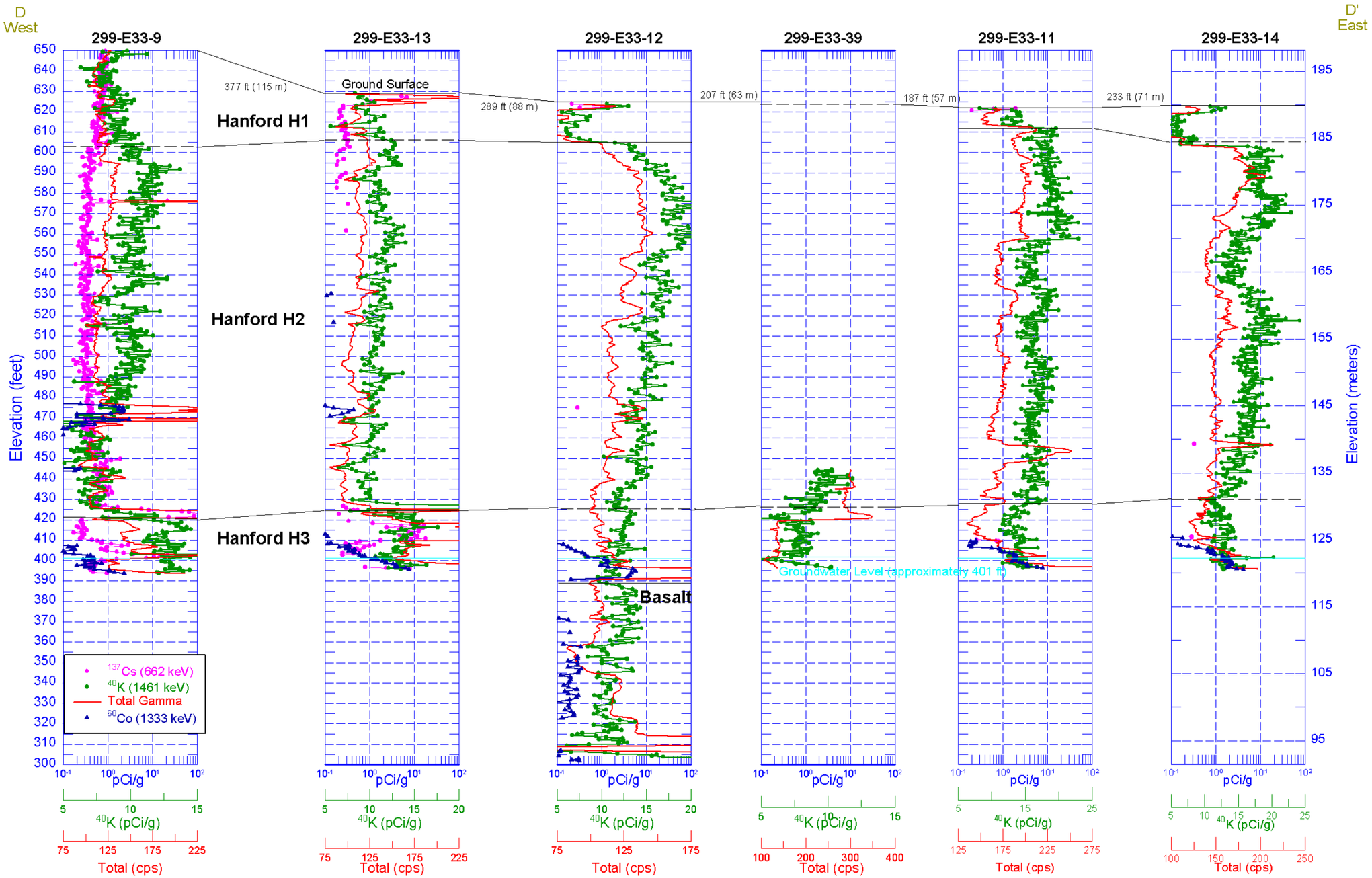


Figure 19. Cross Section D-D' Showing Contamination and Interpreted Stratigraphy Along Selected Groundwater Wells

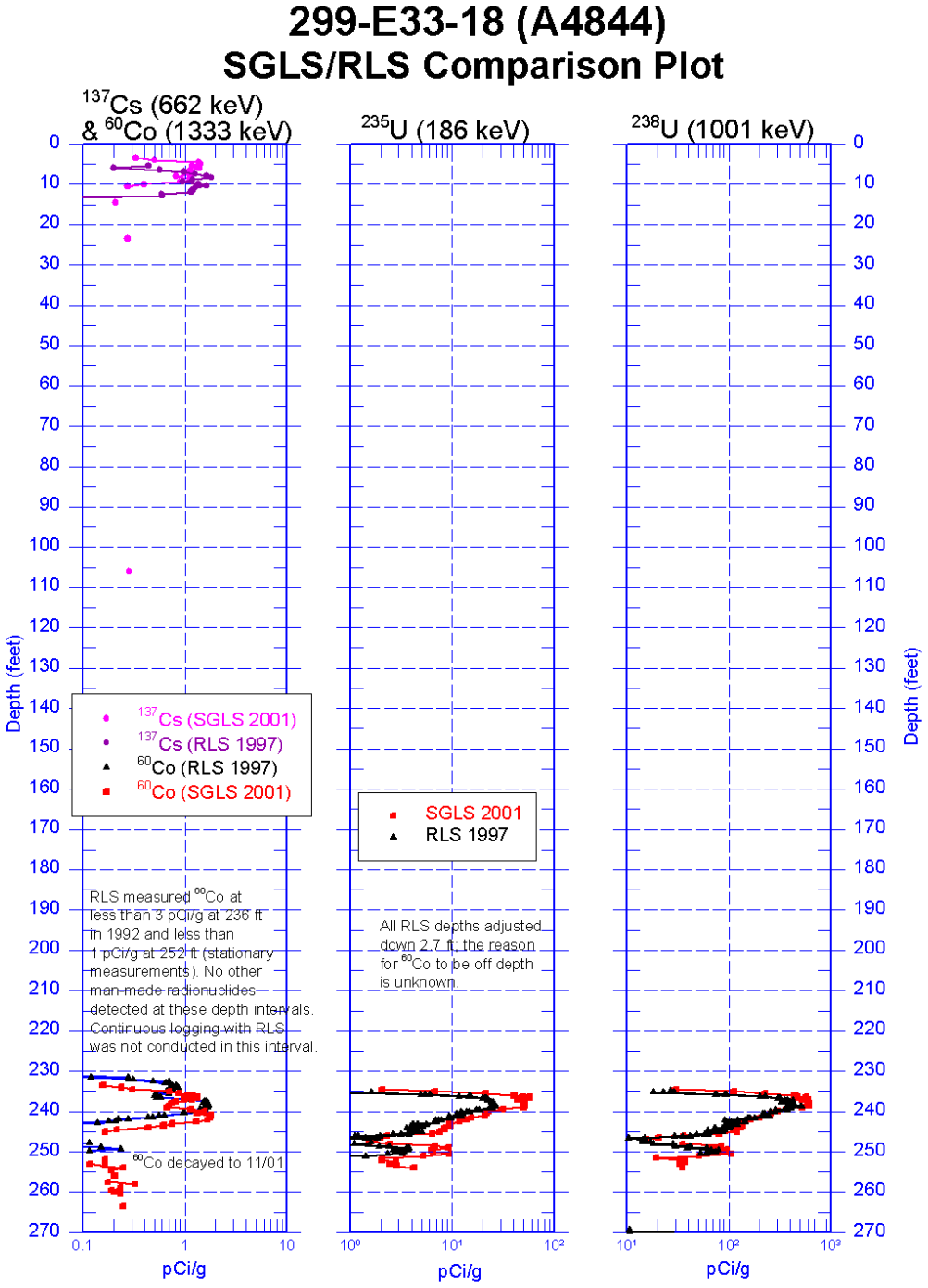


Figure 20. Borehole 299-E33-18 SGLS/RLS Comparison Plot

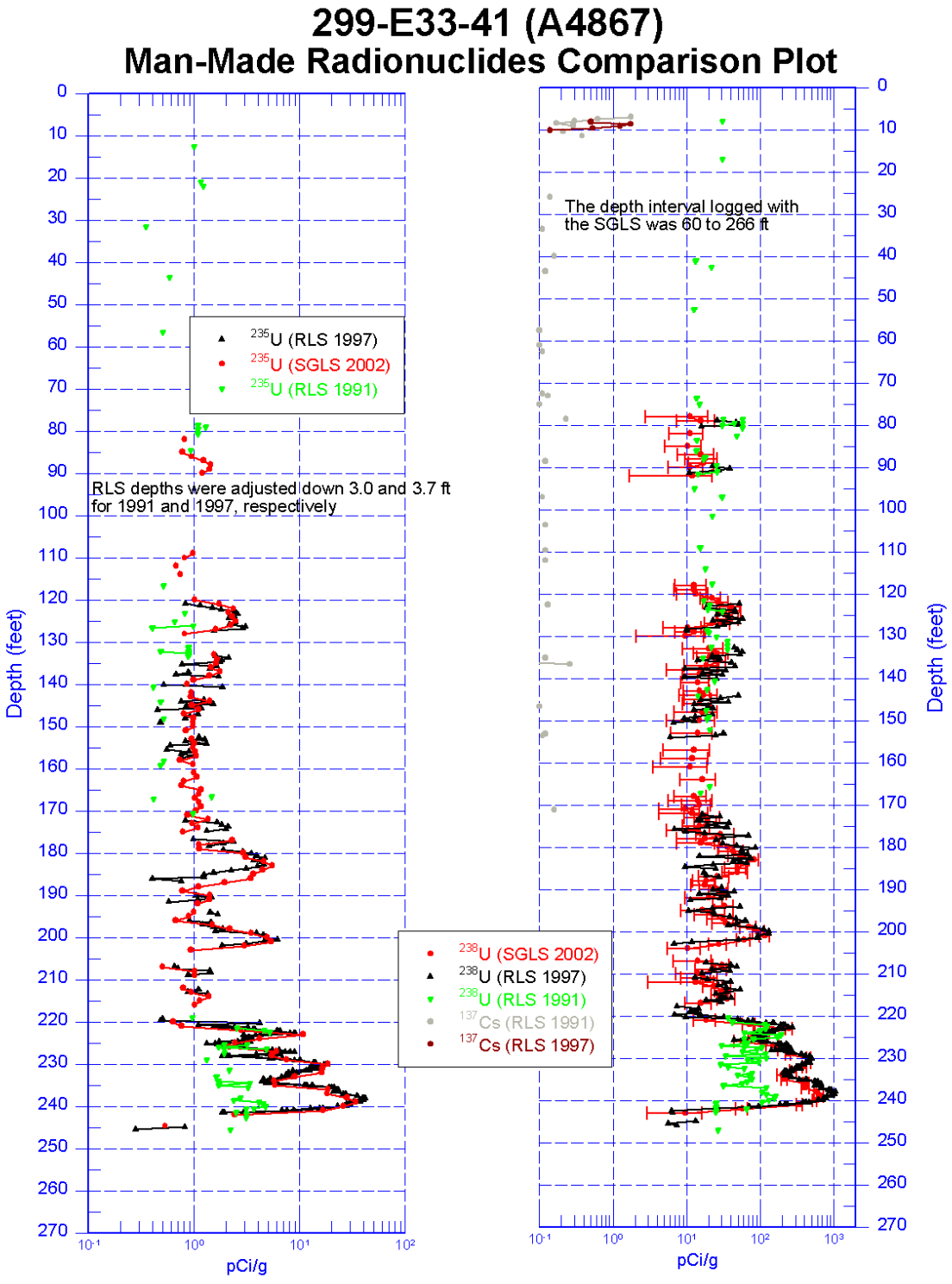
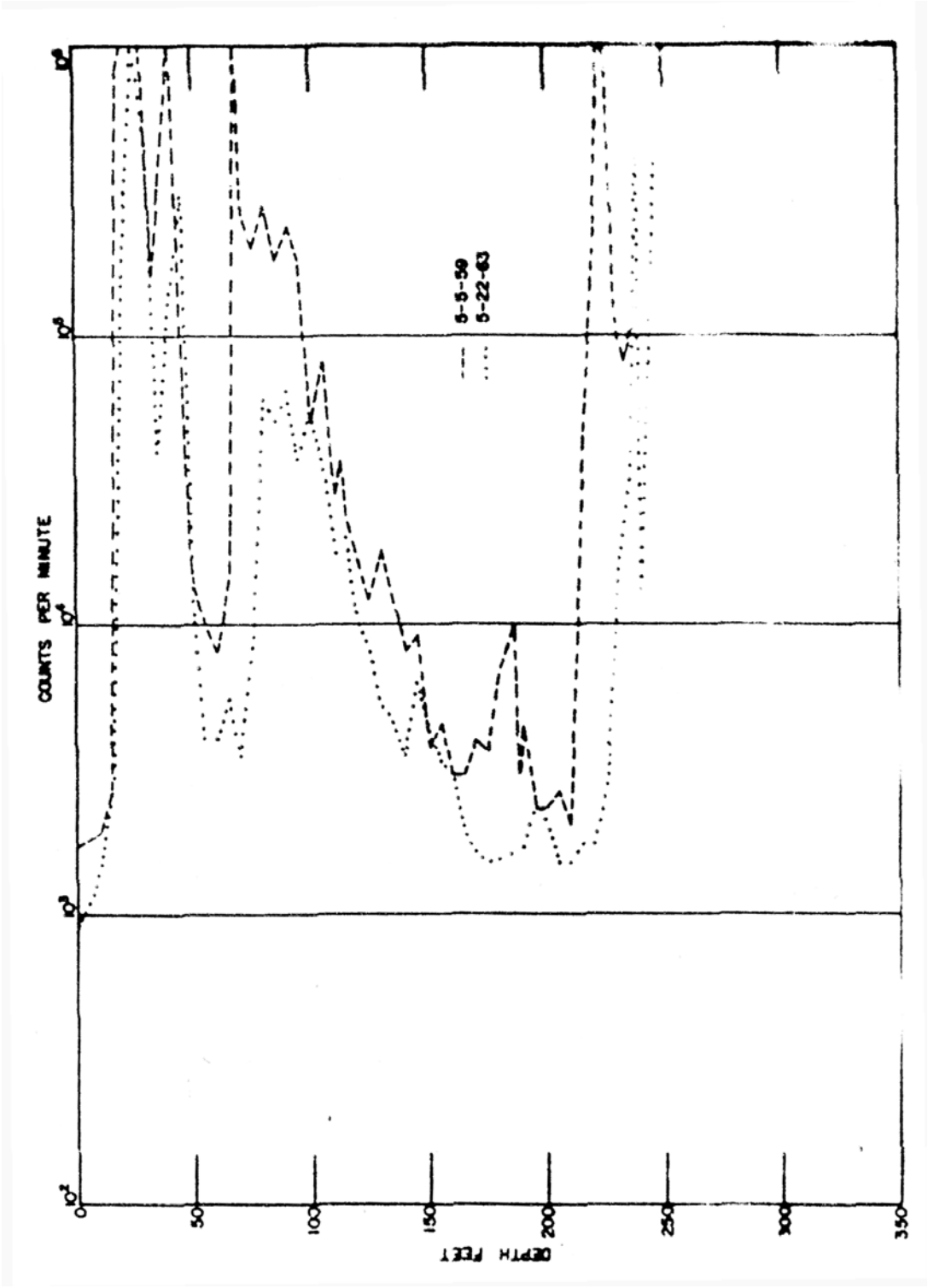
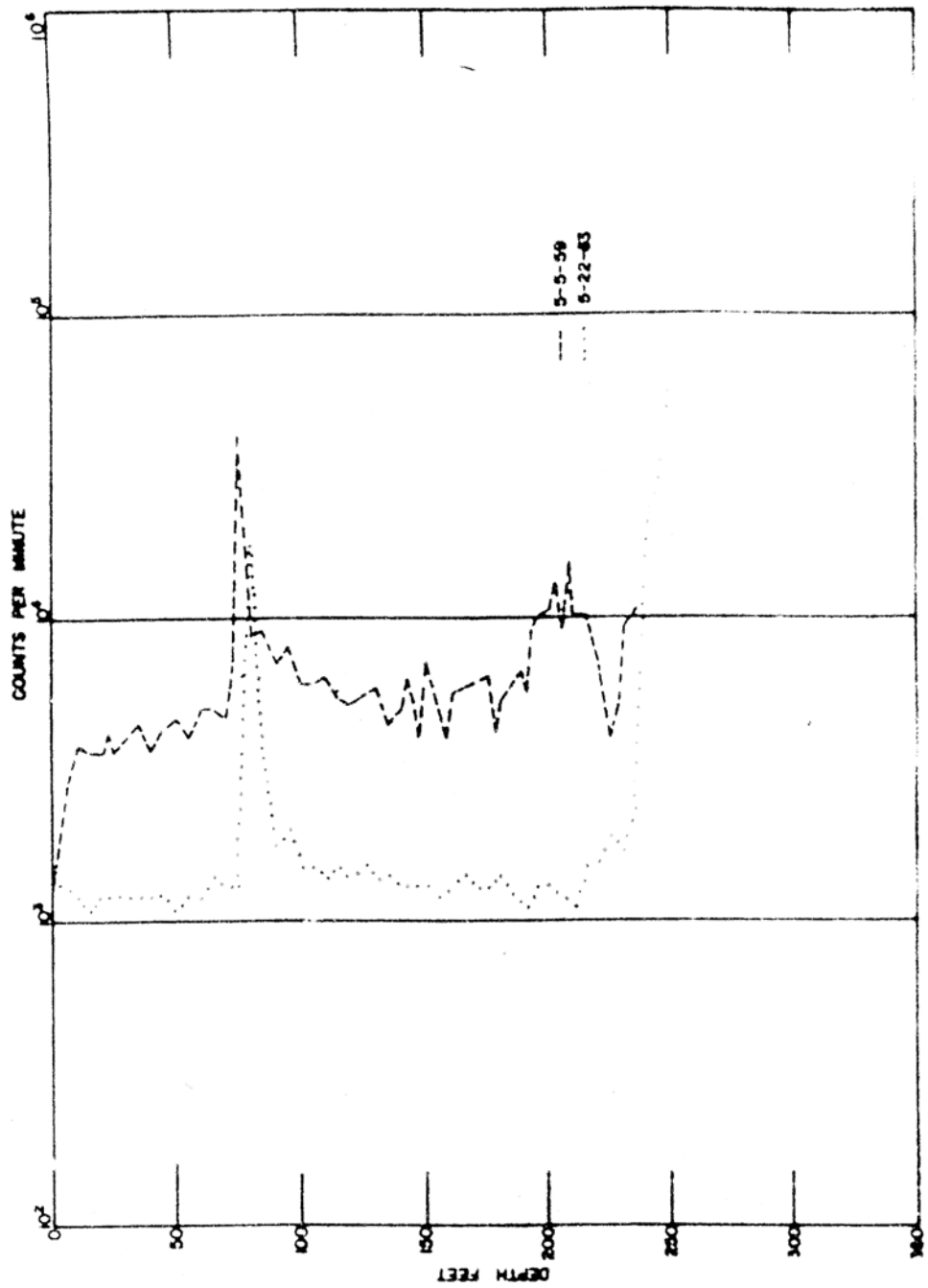


Figure 21. Borehole 299-E33-41 SGLS/RLS Comparison Plot



from Raymond and McGhan (1964)

Figure 22. Borehole 299-E33-16 in the Area of the 216-B-8 Crib and Tile Field



from Raymond and McGhan (1964)

Figure 23. Borehole 299-E33-20 in the Area of the 216-B-11A Reverse Well

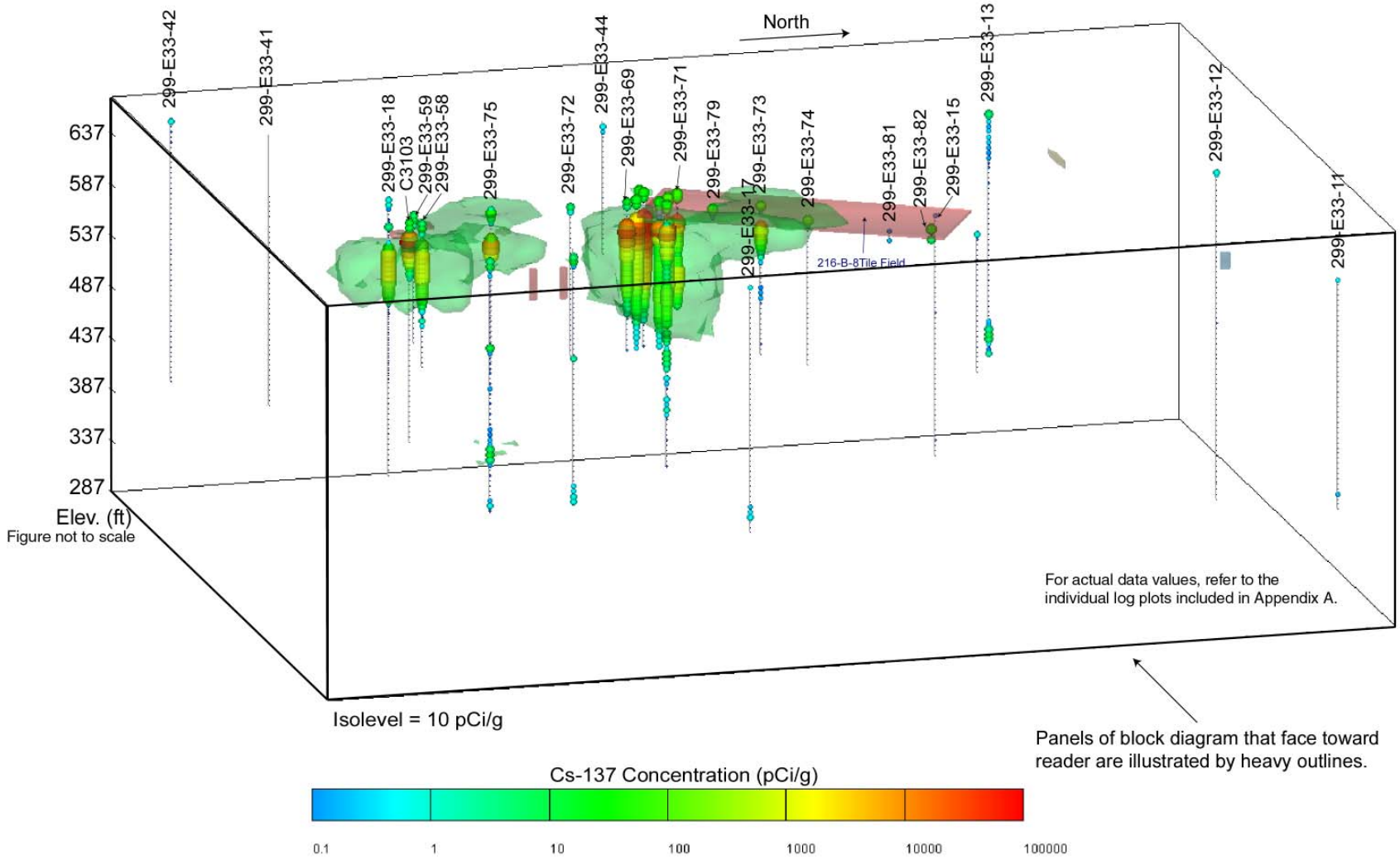


Figure 24. Visualization of Cs-137 Areas of Contamination

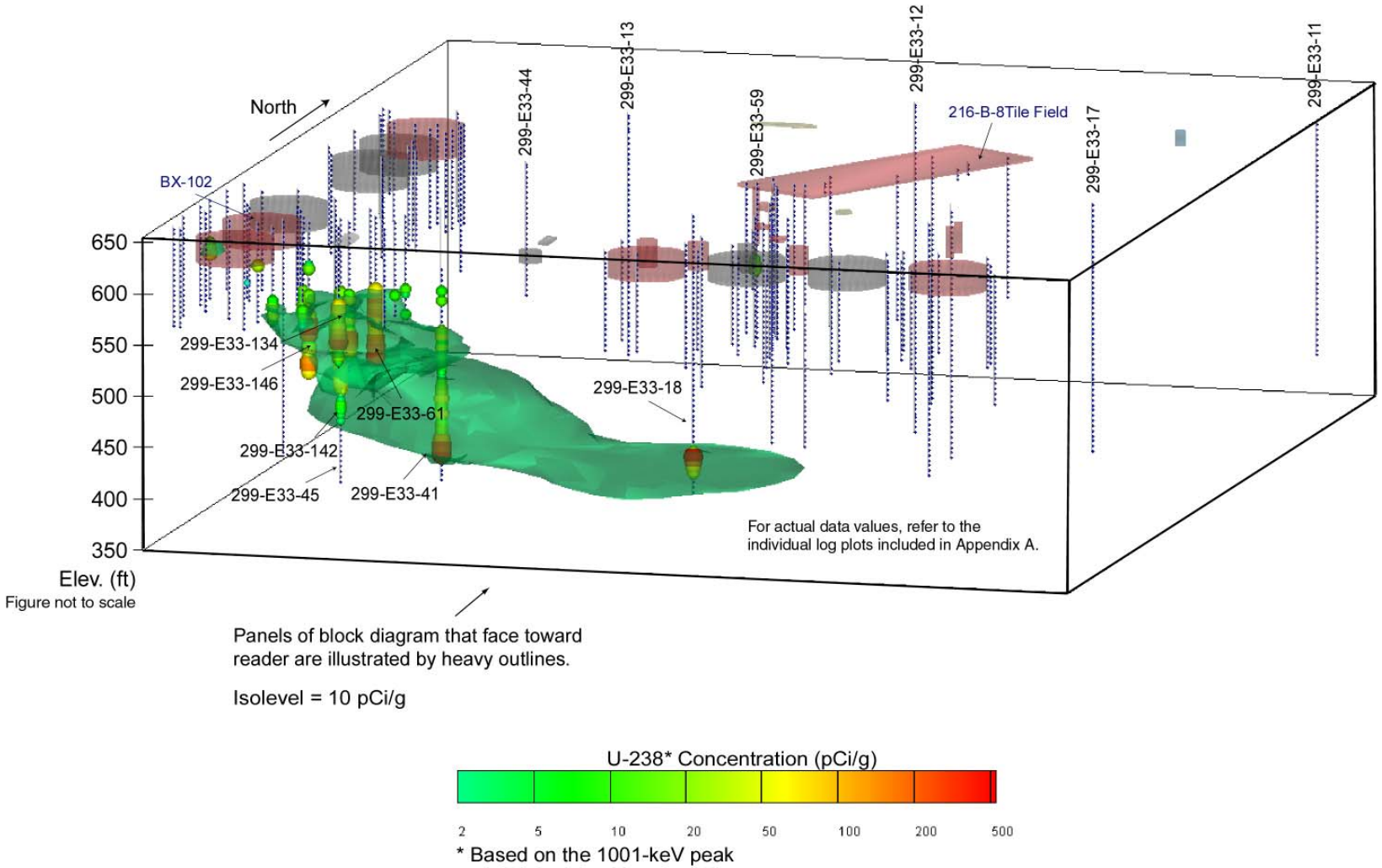


Figure 25. Visualization of an U-238 Area of Contamination

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Appendix A
Spectral Gamma-Ray Logs for Boreholes and Wells in the Vicinity of the 216-B-8 Crib and Adjacent Sites

(included on accompanying CD-ROM)